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INVESTIGATION OF COPPER-SILICON-ALUMINUM ALLOYS WITH AND WITHOUT MANGANESE

(MATERIAL SECTION REPORT No. 178)

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Prepared by E. H. Dix, jr., and A. J. Lyon
Engineering Division, Air Service
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INVESTIGATION OF COPPER-SILICON-ALUMINUM ALLOYS WITH AND WITHOUT MANGANESE.

PURPOSE.

To investigate the mechanical and physical properties and casting qualities of the alloys of copper, silicon, and aluminum, containing from 0 to 9 per cent silicon and from 0 to 6 per cent copper, and to note the effect of the addition of 1 per cent of manganese to certain of these alloys.

CONCLUSIONS.

1. Alloys of aluminum containing 3 to 5 per cent of silicon in combination with copper within the same limits are suitable for the same general casting purposes as alloy No. 1—copper 8 per cent, aluminum 92 per cent—Air Service Specification 11023. The fundamental value of the alloys containing silicon, and their advantage over aluminum alloy No. 1, lies in their relative freedom from casting defects, such as cracks, due to solidification shrinkage, hot shortness, draws, and porosity.

2. One per cent of added manganese slightly raises the strength at high temperature but impairs the casting properties. Its use in the copper-silicon-aluminum alloys is not justified.

3. The mechanical properties of the copper-silicon alloys are about the same as those of aluminum alloy No.1. The ductility is slightly better and the solidification shrinkage and specific gravity slightly less. The machining properties are inferior to alloy No. 1. The best alloys of this series, with regard to machinability, are those with copper corresponding to the upper limits, and silicon to the lower limits of the compositions stated above. Since the silicon decreases the elongation at a slower rate than the copper, an alloy of 3 per cent copper, 4 per cent silicon, and balance aluminum has been chosen for general casting purposes.

4. The following metallographic constituents have been observed in specimens of this series of alloys:

(*a*) $CuAl_2$ aluminum eutectic.

(*b*) Silicon-aluminum eutectic.

(*c*) Needles, generally supposed to be $FeAl_3$.

(*d*) A probable compound of iron and silicon and perhaps aluminum, which resembles in color the characteristic needles of what has been called $FeAl_3$.

(*e*) A constituent which usually appears as blue-gray cubes.

(*f*) With the addition of manganese, a constituent of a peculiar swastika form appears which was not identified.

MATERIAL.

Grade 2 (Specification 11011-A), aluminum ingot (Melt 920), of the following analysis—silicon 0.99, copper 0.32, iron 0.51, manganese nil, aluminum (by difference) 98.18—was used throughout this investigation. It will be noted that silicon is the only impurity in excess. A silicon-aluminum hardener (Melt 958) was purchased from the Electro Metallurgical Corporation, Niagara Falls, N. Y., and had the following analysis: Silicon 60.51, copper 0.30, iron 1.22, aluminum (by difference) 37.97. The 50-50 copper-aluminum hardener (Melt 1006) was made in this foundry and had the following chemical analysis: Copper 49.55, silicon 0.17, iron 0.21, aluminum (by difference) 50.07. The manganese (94–95 per cent pure) was obtained from the Goldschmidt Thermit Corporation and is supposed to be practically free from iron and carbon. No analysis was made.

PROCEDURE.

MANUFACTURE OF HARDENERS.

The manganese was introduced in the form of a 90–10 aluminum-manganese hardener. A 10-pound melt of this hardener was made by melting 1 pound of manganese and 4½ pounds of aluminum ingot together in the small Ajax electric induction furnace. It was necessary to heat this charge to 1,900° F. before the manganese and aluminum would alloy. The balance of the aluminum ingot was then added, and after thorough stirring poured at a temperature of 1,600° F. into cast-iron molds. The analysis obtained on a sample from this melt (Melt 1047) follows: Copper 0.17, silicon 0.40, iron 0.54, manganese 10.10, aluminum by difference.

A 50–50 copper-aluminum hardener was used to introduce the copper in the alloys. This was made according to the usual foundry procedure; the copper and half of the aluminum were melted separately and the molten aluminum poured into the copper, the balance of the aluminum being added cold to act as a chill.

METHOD OF MAKING ALLOYS.

Fifteen alloys containing different combinations of silicon and copper, with and without manganese, were made in melts of 40 pounds each. The required percentages of hardeners and aluminum ingot were all charged together in a No. 40 plumbago crucible and melted in an oil-fired furnace. Temperature measurements were made by a bare chromel-alumel thermocouple (No. 8 gauge), immersed in the molten metal, and used in conjunction with a Hoskins high-resistance millivoltmeter. The melts were heated to, but not above, 1,400° F. in order to allow thorough alloying. A uniform pouring temperature of 1,300° F. was maintained. The time in the furnace averaged about 1 hour.

The following test specimens were poured in green sand from each melt:

Six molds, pattern TB-1, tension tests "as cast" and at high temperature.

Two molds, pattern TB-1A, tension tests "machined."

Two molds, pattern TB-4, coefficient of expansion tests.

One mold, pattern TB-6, impact tests.

Three molds, pattern PC-2, porosity tests.

Three shrinkage bars (see fig. 1).

One mold, hot shortness bar (see fig. 2).

Modulus of elasticity specimens were cast from remelts of the gates and risers of the above as follows:

One mold, pattern TB-13, "as cast" specimen.

One mold, pattern TB-14, "machined" specimen.

PHYSICAL TESTING.

The following tests were made by the Physical Testing Branch:

Five tension tests, "as cast," at normal temperatures, pulled in wedge grips.

Five tension tests, "as cast," at 300° F., pulled in self-aligning adapters.

Five tension tests, "as cast," at 600° F., pulled in self-aligning adapters.

Three tension tests, "as cast," after 30 days' aging.

Five tension tests, "as cast," after nine months' aging.[1]

Six tension tests, on "machined" specimens, at normal temperature.

Twelve Charpy impact tests on standard 10 mm. square specimens with 2 mm. diameter drilled notch 5 mm. deep.

Three shrinkage test measurements.

Three porosity tests.

One hot shortness test.

The last four tests are the only ones which require a description in this report, all of the others being performed according to standard methods. The shrinkage test bar is shown in Figure 1. This bar is cast in green sand between graphite plates set exactly 12 inches apart by a master bar. The final length of the bar, after cooling, is measured by a micrometer and the difference between this length and the length of a master bar taken as the shrinkage in inches per foot for the alloy.

The porosity tests were made in accordance with the procedure described in Material Section Report No. 160, McCook Field Serial No. 1882.

Figure 2 shows the apparatus devised for testing the hot shortness of this series of alloys. By casting the test bar around two fixed lugs, 12 inches apart, the normal shrinkage of the metal is prevented.

The modulus of elasticity tests were made in the usual way, and the deformations were taken by a Ewing extensometer.

The coefficient of expansion and thermal conductivity determinations were made by the Bureau of Standards, the former by their standard method and the latter by a method described by them in the following:

"METHOD OF TEST.

"The specimens were in the form of short cylinders, 1½ inches in diameter and about three-fourths inch long. The ends were ground flat to a few thousandths of a millimeter and the specimen placed between two longer brass cylinders of the same diameter, in such a way that the axes of the three cylinders were in the same straight line. Good thermal contact between the brass and the test material was obtained by wetting the contact surfaces with a dilute solution of glycerin. One end of this system of cylinders was heated electrically and the other end cooled with water in order to produce a temperature gradient along the axis. Since the heat loss from the convex surface of the cylinders is small in comparison with the total heat flow, practically the same amount of heat flows through both brass and specimen, and the ratio of the thermal conductivities of the two materials will be equal to the inverse ratio of the temperature gradients in each. The temperature gradient in the brass on both the hot and cold side of the specimen was measured by means of thermocouples inserted in small holes regularly spaced along the bars, and the temperature of each end of the test cylinder was assumed to be the same as that of the brass in contact with it. Separate experiments had shown that this was the case to about 0.1° C., the limit of precision of measurement with the apparatus used.

"All the samples were compared in this way with the brass, and the latter was in turn compared with several pure metals of known conductivity as a check on the method, and as a means of giving absolute values of thermal conductivity to the various alloys."

RESULTS.

The results of the mechanical properties of these alloys are summarized in Table 1. The detailed results are filed in both the Material Section general file and the Metals Branch file and may be referred to through the melt numbers. Table 2 gives the results of coefficient of expansion tests (Bureau of Standards Report No. Twe 32754). The thermal conductivity results (Bureau of Standards Report No. Tth 33517) are given in Table 3. Table 4 contains the observations made by the machine shop when the test bars of these alloys were machined. Table 5 gives the results of the porosity tests. Table 6 gives the results of the tension tests made on the hot shortness bars. Table 7 gives the averaged results of the Charpy impact tests.

These results are further shown graphically as follows:

Figures 3 to 7 show the effect of composition on tensile strength, elongation, impact, hardness, shrinkage, expansion, and specific gravity.

Figures 8 to 12 show the stress deformation characteristics of these alloys.

Figures 13 and 14 show the effect of copper with and without manganese on the tensile strength and elongation of silicon-aluminum alloys at elevated temperatures.

The metallographic structure of this series is illustrated by 18 micrographs as follows:

Figures 15 and 16 show an average and segregated area of the aluminum ingot used.

Figures 17 to 19, inclusive, show the effects of 3, 6, and 9 per cent silicon on commercially pure ingot.

Figures 20 and 21 show the effect of 4 and 6 per cent copper with 3 per cent silicon on aluminum.

Figure 22 shows the effect of manganese with 3 per cent silicon, 2 per cent copper, on aluminum.

[1] Except Melts 1021 and 1071, which had only 3 and 4 specimens, respectively.

DISCUSSION OF RESULTS.

TENSION TESTS ON "AS CAST" SPECIMENS.

These tests, which were made within 24 hours after casting, show that the addition of silicon up to the limit of these experiments (9 per cent) increases the tensile strength at the expense of the elongation, and the effect of the added silicon is more pronounced below 6 per cent than above. Copper, as is well known, has a similiar effect on the tensile strength and decreases the elongation more rapidly than the silicon, and therefore, due to the combined action of copper and silicon, it is necessary that the total of the two elements be less than 10 per cent. The best combinations of tensile strength and elongation have been obtained with copper and silicon between 3 and 5 per cent each. The alloy of 3 per cent copper and 4 per cent silicon has been used for considerable routine work and has been found to give a good combination of strength and elongation (tensile strength 21,000 pounds per square inch, elongation 2.5 per cent).

TENSION TESTS ON "MACHINED" SPECIMENS.

The tension tests on the machined specimens average about 850 pounds per square inch lower than those tested with the skin on, and the elongation is about the same.

AGING TESTS.

The results obtained on test bars tested 30 days after casting and 9 months after casting show that the aging effect on this series of alloys is negligible. There is only one melt which showed any notable difference, namely, Melt 1048, containing 6.39 per cent copper and 3.90 per cent silicon. This showed an increase in tensile strength in the 9 months' aging tests of about 4,000 pounds per square inch, with about the same elongation. This is, however, probably due to differences in test bars rather than any aging effect.

MODULUS OF ELASTICITY TESTS.

The average modulus of elasticity obtained from the bars "as cast" is 11,500,000 pounds per square inch. The complete stress deformation curves are included in the report. The proportional limit of the alloys, containing from 3 to 5 per cent each of copper and silicon, is about the same as the 8 per cent copper-aluminum alloy (about 6,000 pounds per square inch).

BRINELL AND SCLEROSCOPE HARDNESS TESTS.

The Brinell and scleroscope hardness is increased by the addition of either copper or silicon and also by the addition of both together. In general the hardness values for these alloys are slightly lower than the standard 8 per cent copper-aluminum alloy.

CHARPY IMPACT TESTS.

In the straight silicon-aluminum alloys the impact resistance is apparently reduced by the addition of silicon. In the alloys containing copper the effect of silicon is erratic. The impact resistance seems to be increased by the addition of copper to the silicon-aluminum alloys.

PATTERN SHRINKAGE.

The pattern shrinkage of this whole series of alloys is slightly lower than that of the standard 8 per cent copper-aluminum alloy, the latter having a shrinkage of 0.187 inch per foot as determined in a similar manner.

COEFFICIENT OF EXPANSION.

Coefficient of expansion results show that the expansion is only slightly influenced by the addition of either copper or silicon and that the expansion of this whole series is very close to that of the standard 8 per cent copper-aluminum alloy.

THERMAL CONDUCTIVITY TESTS.

Thermal conductivity tests as made by the Bureau of Standards indicate some small variations in this series, but these variations can not be attributed to the varying percentages of copper and silicon. The values obtained are similar to the value obtained for the 8 per cent copper-aluminum alloy.

MACHINING QUALITIES.

The straight silicon-aluminum alloys machine very poorly. The metal tears in much the same manner as pure aluminum and in addition the particles of silicon shown in Figures 17 to 19 appear to dull the tool very rapidly. The addition of copper improves the machining qualities due to the $CuAl_2$ network shown in Figure 20–A. The alloy of 3 per cent copper and 4 per cent silicon machines fairly well, although not as well as the standard 8 per cent copper-aluminum alloy.

POROSITY TESTS.

This whole series of alloys gave very good results in the porosity tests. The straight silicon-aluminum alloys were exceptionally good.

HOT SHORTNESS TESTS.

The most remarkable feature of this whole series of alloys is their ability to be cast around nonyielding cores without cracking. Only one composition (Melt 1069, Cu 6.29, Si 9.00, Fe 0.66) of this series of alloys cracked under the very severe hot shortness test which has been devised. Further, when these bars were tested, they showed a strength slightly greater than the average for the "as cast" test bars and an elongation slightly lower, as though they had received a certain amount of cold working.

METALLOGRAPHIC STUDY.

The metallography of this series of alloys can be best explained by first considering the structure of the aluminum ingot from which all of the alloys were prepared. A transverse section of the three-fourths-inch diameter end of a specimen cast in green sand according to pattern TB–1 was examined in detail. The constituents found are illustrated in Figures 15 and 16. At 100 X the aluminum solid solution matrix was found to include a network of impurities as shown in Figure 15A. It was noted that near the pipe at the center of the test bar the impurities had segregated in large amounts as illustrated by Figure 16A. Upon examination at 500 X the individual constituents composing the network were distinguishable as shown in Figures 15B and 16B, but these are more easily differentiated

at 1,000 X, as shown by Figures 15C and 16C. The particles appearing black in Figure 15C appear a dark purple under visual examination and the needles which appear in half-tone were a light-gray under visual examination. Figures 16B and 16C show that the network in the segregated area has a distinctly different appearance. The particle shown in Figure 16C appeared the same shade as the needles shown in Figure 15C. Very little of the dark purple constituent was found in this segregated area; the black areas in the particle of Figure 16C are crevices.

The dark purple particles were found to increase with the addition of silicon, and to assume a eutectic network, as shown in Figures 17, 18, and 19. With 3 per cent added silicon, the eutectic particles are very fine, as shown in Figures 17A and 17B. The needles shown in these figures were apparently the same constituent observed in the form of needles in the original ingot. As the per cent of added silicon was increased, some of the areas of eutectic particles became much coarser, as shown in Figures 18A and 18B. It is therefore safe to conclude that the dark purple particles observed in the original ingot and the eutectic noted above are particles of pure silicon, since it is known (references 1 and 2) that silicon does not form a compound with the aluminum. The needles have generally been conceded to be the compound $FeAl_3$. but iron is also thought to form a compound with silicon, containing perhaps some aluminum, which has been called the "X constituent" by other experimenters (references 3 and 4). It seems reasonable to conclude, however, that if iron forms two separate constituents, the crystal habits of these constituents are probably different, so that the $FeAl_3$ may always form needles, whereas the other compound may take an entirely different form or forms. Considerable attention was paid to this point, but it seemed to be impossible to differentiate between the needles and several other constituents by any means at present available. A constituent having the same color but a dendritic formation is shown in Figures 21A and 21B, and further with the addition of manganese a very similar constituent was found to occur in a characteristic swastika form, as shown in Figures 22A and 22B. Thus, it was impossible to distinguish by color or etching characteristics between the needles in Figure 15C or the particles in Figure 16C or the dendritic structure in Figure 21B or the swastika form in Figure 22B. It is recognized that a constituent may occur in different forms due to many influences, and as a result of a prolonged examination of these specimens at 1,000 X, this grayish constituent must be recognized as occurring in four distinct forms probably representing three different constituents—the compound $FeAl_3$, the "X" constituent, and a constituent due to the presence of manganese.

In all of these alloys bluish-gray cubes, as illustrated in Figures 19A and 19B, were recognized. These seem to be more numerous in the higher silicon alloys and may perhaps be primary silicon crystals or particles due to some unknown impurity in the silicon hardener.

In the alloys containing copper the $CuAl_2$ compound was easily distinguished due to previous work on these alloys. In the unetched specimen it appeared a clear white with a pink tinge and was readily distinguished from the silicon or the iron constituents. It was also identified by the method of etching described by Hanson (reference 5), which consists in immersing the specimen in 20 per cent aqueous HNO_3 at 70° C. followed by a quench in cold water. This colors the $CuAl_2$ from a chocolate to black, depending upon the time of immersion in the acid. Figures 20A and 20B show the structure of the alloy containing 4 per cent copper and 3 per cent silicon. In Figure 20B silicon appears dark and the $CuAl_2$ particles light. In addition to these two constituents, there will be noted particles in half tone which appear as needles and elongated globules. This constituent under visual examination has the characteristic gray color which distinguishes the iron compound, but it is not possible to say whether it is $FeAl_3$ or the "X constituent."

The segregation shown in Figures 15 and 16 gives evidence of the value of metallography as a check on chemical analysis, for a sample taken from the segregated area of Figure 16 would give a very erroneous idea of the average composition of the specimen.

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(4) P. D. Merica, R. G. Waltenberg, and J. R. Freeman, jr., "The Constitution and Metallography of Aluminum and Its Light Alloys with Copper and with Magnesium," Scientific Paper No. 337, U. S. Bureau of Standards, 1919.

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TABLE 1.—*Summary of results.*

	Yield point, pounds per square inch.	Tensile strength, pounds per square inch.	Elongation, per cent in 2 inches.	Modulus of elasticity X 10^6.	Brinell, 500 kg.	Scleroscope.	Charpy impact.	Specific gravity.	Shrinkage, inches per foot.
Melt 1010—Cu 0.41, Si 4.12, Fe 0.59.									
"As cast"		18,120	4.9	...	35.2	8.5	...	2.65	0.164
"Machined"	10,500	17,180	5.3	...	33.8	7.2	2.13	...	...
30 days' aging		19,520	5.3	...	34.8	9.7	...	...	...
9 months' aging		19,260	4.0	...	34.5	...	...	...	...
Modulus spec.:									
"As cast"		17,350	.75	12.3	(Melt 1089 Elongation in 8 inches.)				
"Machined"		15,520	3.50	11.4					

Table 1.—*Summary of results*—Continued.

	Yield point, pounds per square inch.	Tensile strength, pounds per square inch.	Elongation, per cent in 2 inches.	Modulus of elasticity, X 10⁶.	Brinell, 500 kg.	Sclero-scope.	Charpy impact.	Specific gravity.	Shrinkage, inches per foot.
Melt 1012—Cu 0.42, Si 6.20, Fe 0.90.									
"As cast"		19,800	4.2		36.7	9.3		2.63	0.161
"Machined"	15,830	18,680	4.2		36.3	8.1	2.07		
30 days' aging		21,520	4.2		38.0	11.0			
9 months' aging		19,800	4.25		35.0				
Modulus spec.:									
"As cast"		18,440	2.75	11.4	(Elongation in 8 inches.)				
"Machined"		17,020	2.5	10.5					
Melt 1016—Cu 0.34, Si 9.34, Fe 0.73.									
"As cast"		18,986	2.8		37.0	10.0		2.60	0.163
"Machined"	15,990	18,610	3.0		34.8	7.9	1.78		
30 days' aging		20,120	2.5		35.0	11.0			
9 months' aging		18,430	3.0		41.0				
Modulus spec.:									
"As cast"		19,470	2.25	12.3	(Elongation in 8 inches.)				
"Machined"		16,930	1.75	10.8					
Melt 1021—Cu 2.15, Si 2.66, Fe 0.62.									
"As cast"		20,260	3.5		42.4	9.4		2.70	0.171
"Machined"	16,680	20,180	3.17		44.8	8.9	2.50		
30 days' aging		22,050	3.3		39.0	11.0			
300° F.		20,070	3.5						
600° F.		10,640	12.0						
Modulus spec.:									
"As cast"		19,260	1.88	11.4	(Elongation in 8 inches.)				
"Machined"		18,140	1.62	10.6					
Melt 1025—Cu 2.32, Si 6.69, Fe 0.65.									
"As cast"		19,882	2.0		50.0	12.0		2.67	0.158
"Machined"	17,960	20,410	2.5		50.0	10.6	2.31		
30 days' aging		21,660	1.3		51.0	12.3			
300° F.		19,360	2.5						
600° F.		11,770	7.4						
Modulus spec.:									
"As cast"		22,230	1.62	11.4	(Elongation in 8 inches.)				
"Machined"		19,640	1.12	12.2					
Melt 1026—Cu 2.29, Si 9.58, Fe 0.71.									
"As cast"		21,610	1.5		55.4	12.4		2.63	0.159
"Machined"	18,390	22,150	2.3		51.3	10.7	2.53		
30 days' aging		22,150	2.2		47.0	16.0			
300° F.		20,800	2.0						
600° F.		10,530	4.5						
Modulus spec.:									
"As cast"		20,770	1.0	11.4	(Melt 1141—Elongation in 8 inches.)				
"Machined"		19,360	.75	11.4					
Melt 1036—Cu 4.25, Si 3.41, Fe 0.74.									
"As cast"		21,740	2.2		54.6	13.0		2.72	0.163
"Machined"		21,300	1.1		55.0	13.0	2.18		
30 days' aging		23,970	1.7		60.0	14.0			
9 months' aging		23,360	1.5		55.0				
Modulus spec.:									
"As cast"		19,870	.38	11.4	(Melt 1102—Elongation in 8 inches.)				
"Machined"		21,210	.75	11.8					
Melt 1042—Cu 4.17, Si 4.92, Fe 0.72.									
"As cast"		22,170	1.4		59.4	13.0		2.69	0.158
"Machined"	15,710	22,420	1.0		59.0	13.7	2.74	2.70	
30 days' aging		24,550	1.7		65.0	15.0		2.71	
300° F.		22,880	2.2						
600° F.		13,410	5.3						
Modulus spec.:									
"As cast"		22,190	.75	11.0	(Melt 1142—Elongation in 8 inches.)				
"Machined"		20,800	.62	11.4					

TABLE 1.—*Summary of results*—Continued.

	Yield point, pounds per square inch.	Tensile strength, pounds per square inch.	Elongation, per cent in 2 inches.	Modulus of elasticity, X 10⁶.	Brinell, 500 kg.	Sclero-scope.	Charpy impact.	Specific gravity.	Shrinkage, inches per foot.
Melt 1044—Cu 4.26, Si 10.12, Fe 0.70.									
"As cast"		22,540	0.9		65.0	15.0		2.69	0.151
"Machined"	16,880	21,500	1.4		64.0	14.3	2.46	2.67	
30 days' aging		23,640	0.5		70.0	16.3		2.67	
9 months' aging		23,850	1.3		70.0				
Modulus spec.:									
"As cast"		18,420	.25	11.4	(Melt 1144—Elongation in 8 inches.)				
"Machined"		20,220	.88	12.3					
Melt 1048—Cu 6.39, Si 3.90, Fe 0.77.									
"As cast"		23,210	0.9		59	14		2.74	0.159
"Machined"	12,070	20,290	1.17		65	16	2.63	2.75	
30 days' aging		23,380	1.0		65	18		2.74	
9 months' aging		27,260	1.16		68				
Modulus spec.:									
"As cast"		21,370	0.62	11.2	(Melt 1166—Elongation in 8 inches.)				
"Machined"		20,080	0.6	10.7					
Melt 1065—Cu 6.39, Si 6.28, Fe 0.51.									
"As cast"		24,960	0.4		59	14		2.74	0.156
"Machined"	17,350	24,210	1.17		63.5	16	2.45	2.76	
30 days' aging		21,160	.5		71.3	15.6		2.75	
300° F		23,200	1.5						
600° F		13,850	2.8						
Modulus spec.:									
"As cast"		20,290	0.5	10.8	(Melt 1165—Elongation in 8 inches.)				
"Machined"		18,910	0.4	11.4					
Melt 1069—Cu 6.29, Si 9.00, Fe 0.66.									
"As cast"		24,170	1.0		56	17			0.150
"Machined"		20,145	1.25		66	15.6	2.61	2.73	
30 days' aging		24,990	1.3		74	16.7		2.72	
9 months' aging		25,020	1.0		80.0				
Modulus spec.:									
"As cast"		19,560	0.25	11.4	(Melt 1164—Elongation in 8 inches.)				
"Machined"		20,920	0.4	11.4					
Melt 1071—Cu 2.33, Si 3.86, Fe 0.65, Mn 0.87.									
"As cast"		22,010	2.5		40	10			0.175
"Machined"		20,675	2.25		49.5	11	2.41	2.67	
30 days' aging		22,580	3.5		54.7	11.3		2.69	
300° F		20,940	3.5						
600° F		11,760	8.3						
Modulus spec.:									
"As cast"		20,160	1.5	10.5	(Melt 1163—Elongation in 8 inches.)				
"Machined"		18,690	1.5	11.2					
Melt 1073—Cu 2.40, Si 9.97, Fe 0.63, Mn 0.67.									
"As cast"		22,570	1.4		47	16		2.65	0.153
"Machined"		20,480	1.5		46.5	11.2	2.42	2.62	
30 days' aging		20,980	1.5		56	13.3		2.63	
300° F		21,590	1.7						
600° F		11,890	4.6						
Modulus spec.:									
"As cast"		21,020	1.0	11.4	(Melt 1157—Elongation in 8 inches.)				
"Machined"		20,370	1.12	11.4					
Melt 1076—Cu 2.20, Si 9.56, Fe 0.97, Mn 0.71.									
"As cast"		22,190	1.5		42.6	17		2.64	0.153
"Machined"		20,270	2.0		49.5	12	2.35	2.62	
30 days' aging		22,440	2.0		57	14.7		2.64	
300° F		20,150	1.5						
600° F		12,510	3.9						
Modulus spec.:									
"As cast"		21,800	1.25	12.3	(Melt 1156—Elongation in 8 inches.)				
"Machined"		19,600	0.9	11.4					

TABLE 2.—*Coefficient of expansion.*

(Bureau of Standards Report—Twe 32754.)

Melt No.	Copper.	Silicon.	Manganese.	Average coefficients of expansion.[1]			
				20° to 100° C.	100° to 200° C.	200° to 300° C.	20° to 300° C.
1010	0.41	4.12	....	0.0000222	0.0000240	0.0000258	0.0000241
1012	.42	6.20	....	.0000217	.0000232	.0000251	.0000234
1016	.34	9.34	....	.0000211	.0000226	.0000247	.0000229
1021	2.15	2.66	....	.0000234	.0000243	.0000253	.0000244
1025	2.32	6.69	....	.0000207	.0000226	.0000244	.0000227
1026	2.29	9.58	....	.0000218	.0000235	.0000247	.0000235
1036	4.25	3.41	....	.0000224	.0000242	.0000254	.0000241
1042	4.17	4.92	....	.0000214	.0000234	(2)	....
				.0000215	.0000230	.0000246	.0000231
1044	4.26	10.12	....	.0000204	.0000223	.0000238	.0000223
1048	6.39	3.90	....	.0000218	.0000238	.0000247	.0000236
1035	6.39	6.28	....	.0000204	.0000220	.0000237	.0000221
1069	6.29	9.00	....	.0000206	.0000224	.0000231	.0000222
1071	2.33	3.86	0.87	.0000222	.0000243	.0000245	.0000238
1073	2.40	9.97	.67	.0000208	.0000222	.0000237	.0000223
1076	2.20	9.56	.71	.0000204	.0000224	.0000241	.0000224

[1] Before the thermal expansion tests, these samples were heated to 400° C. and then allowed to cool in furnace.
[2] Observation wire broke at about 300° C. The results obtained on a repeated heating are given in the next line.

TABLE 3.—*Thermal conductivity.*

(Bureau of Standards Report—Tth 33517.)

Melt No.	Copper.	Silicon.	Manganese.	Tin.	Conductivity.[1]	Jaeger and Diesselhorst values.
1395[2]	....	....	....	......	0.40	....
1397	7.49	0.39	0.47	......	.30	....
1400	9.95	.37	....	......	.32	....
1325	2.15	2.66	....	......	.29	....
1324	3.05	4.02	....	......	.32	....
1394	4.17	4.92	....	......	.30	....
1326	2.33	3.86	.87	......	.28	....
1327	6.85	.39	....	0.88	.36	....
99.7% Al	....	....	....	......	.52	0.48
Zinc	....	....	....	......	....	.265
Tin	....	....	....	......	.16	.153
Lead	....	....	....	......	.085	.082

[1] Zinc used as standard—conductivity 0.265 calories $sec.^{-1}$ $deg.^{-1}$ $cm.^{-1}$.
[2] Aluminum 99+.

TABLE 4.—*Machining tests.*

(Cutting speed, 95 feet per minute; revolutions per minute, 250.)

Melt No.	Copper.	Silicon.	Manganese.	Roughing cut.	Finishing cut.
1010	0.41	4.12	....	Rough cutting (tears, brittle).	Hard to polish (scratches).
1012	.42	6.20	....	Rough cutting (tears).	Do.
1016	.34	9.34	....	Rough cutting (deep tool marks).	Do.
1021	2.15	2.66	....	Moderately soft...	Polishes better (tool marks).
1025	2.32	6.69	....	.....do............	Polishes better (smooth cutting).
1026	2.29	9.58	....	.....do............	Do.
1036	4.25	3.41	....	.....do............	Do.
1042	4.17	4.92	....	.....do............	Polishes better (scratches due to pinholes).
1044	4.26	10.12	....	Soft cutting.......	Polished easy, but scratches (due to pinholes).
1048	6.39	3.90	....	.....do............	Do.
1065	6.39	6.28	....	.....do............	Do.
1069	6.29	9.00	....	.....do............	Do.
1071	2.33	3.86	0.87	.....do............	Polishes easy.
1073	2.40	9.97	.67	.....do............	Smooth cutting, polishes well.
1076	2.20	9.56	.71	.....do............	Do.

TABLE 5.—*Porosity tests.*

Specimen No.	Porosity number (seconds for 1000 cc.).			Thickness after machining all over (inch).	
	As cast.	Machined inside.	Machined all over.	Walls.	Bottom.
1010–13	No leak.	No leak.	No leak.	0.095	0.107
1010–14	No leak.	9,480	6,900	.095	.092
1010–15	No leak.	No leak.	No leak.	.092	.104
1012–1	No leak.	No leak.	No leak.	.110	.107
1012–2	1,045	638	615	.095	.112
1012–3	No leak.	No leak.	No leak.	.105	.103
1016–1	13,680	No leak.	12,000	.100	.098
1016–2	Trace.	Trace.	No leak.	.100	.103
1016–3	Trace.	No leak.	180,000	.095	.119
1021–1	6,235	4,470	30,000	.095	.117
1021–2	389	5,233	4,250	.110	.097
1021–3	216	808	1,020	.100	.116
1025–1	Trace.	No leak.	30,000	.095	.105
1025–2	414	310	146	.090	.087
1025–3	772	4,310	30	.095	.064
1026–1	No leak.	Trace.	1,590	.100	.088
1026–2	Trace.	6,470	120,000	.110	.085
1026–3	7,962	Trace.	60,000	.115	.104
1036–1	152	182	248	.088	.112
1036–2	No leak.	No leak.	No leak.	.095	.104
1036–3	No leak.	Trace.	60,000	.095	.091
1042–1	1,420	No leak.	6,000	.100	.115
1042–2	275	132	440	.090	.098
1042–3	No leak.	No leak.	No leak.	.095	.098
1044–1	No leak.	No leak.	425	.100	.107
1044–2	25,500	No leak.	6,000	.090	.128
1044–3	585	572	840	.100	.111
1048–1	No leak.	No leak.	930	.105	.105
1048–2	4,625	18,150	20,000	.110	.105
1048–3	2,530	233	188	.095	.086
1065–1	No leak.	120,000	No leak.	.100	.128
1065–2	No leak.	5,700	6,000	.090	.098
1065–3	2,965	2,015	386	.090	.095
1069–1	No leak.	5,880	20,000	.072	.108
1069–2	60,000	120,000	2,600	.110	.103
1069–3	No leak.	60,000	30,000	.080	.118
1071–1	No leak.	No leak.	No leak.	.105	.118
1071–2	No leak.	No leak.	No leak.	.095	.097
1071–3	No leak.	No leak.	No leak.	.090	.115
1073–1	706	750	120	.090	.103
1073–2	120,000	5,100	600,000	.085	.096
1073–3	No leak.	60,000	1,230	.095	.061
1076–1	No leak.	No leak.	1,360	.075	.125
1076–2	610	350	305	.085	.096
1076–3	No leak.	20,000	6,000	.088	.108

TABLE 6.—*Tension tests on hot shortness bars.*

Melt No.	Tensile strength, pounds per square inch.	Elongation, in 2 inch, per cent.	Brinell, 500 kg.	Scleroscope.
1010	18,140	3.5	25.7	[1] 12
1012	20,970	4.0	36	8
1016	19,560	2.0	40	11
1021	17,850	....	42	11.5
1025	21,940	2.0	47	12
1026	20,690	1.25	48	13
1036	23,410	2.0	50	12
1042	24,210	1.0	54	14
1044	24,440	0.5	50	15
1048	24,570	0.5	49	14
1065	24,960	2.0	59	14
1071	21,750	1.5	37.6	11
1073	24,100	1.0	53	16
1076	22,180	1.5	50	17

[1] Melt 1089.

Note: Test bar from Melt 1069 cracked in mold.

TABLE 7.—*Charpy impact results (foot-pound).*

Melt No.	Bar number.[1]				Average.
	A	B	C	D	
1010	2.14	2.14	2.18	2.08	2.14
1012	2.08	2.13	2.01	2.08	2.07
1016	1.91	1.84	1.61	1.76	1.78
1021	2.43	2.76	2.37	2.45	2.50
1025	2.40	2.23	2.23	2.39	2.31
1026	2.94	2.05	2.39	2.73	2.53
1036	1.92	2.13	2.07	2.39	2.12
1042	2.77	2.67	2.71	2.83	2.74
1044	2.42	2.52	2.39	2.54	2.46
1048	2.54	2.42	2.77	2.71	2.63
1065	2.40	2.41	2.24	2.76	2.45
1069	2.73	2.58	2.47	2.65	2.61
1071	2.45	2.40	2.26	2.53	2.41
1073	2.51	2.25	2.16	2.75	2.42
1076	2.16	2.13	2.58	2.54	2.35

[1] The result for each bar is average of three specimens.

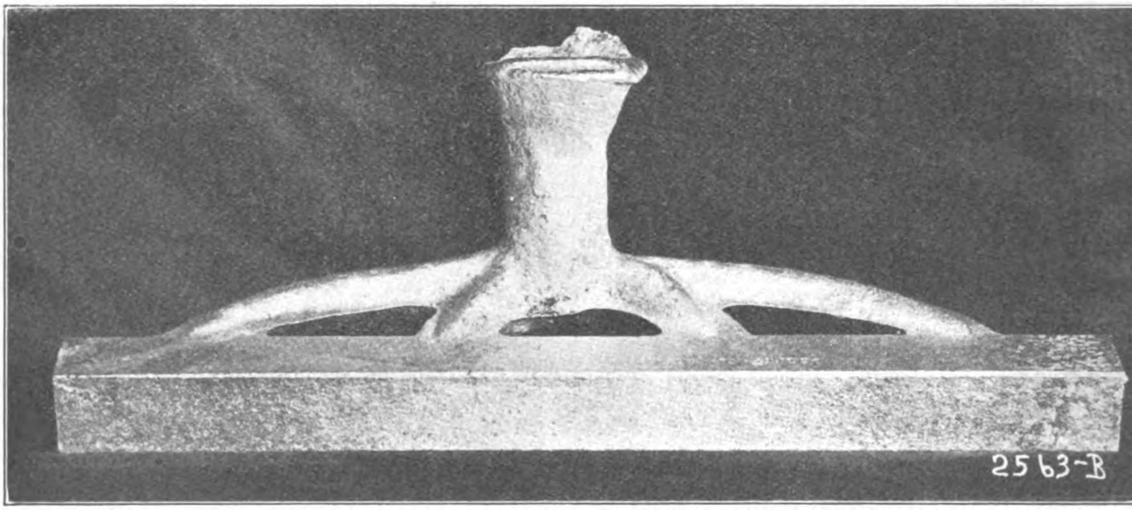


FIG. 1.—Method of casting shrinkage bars.

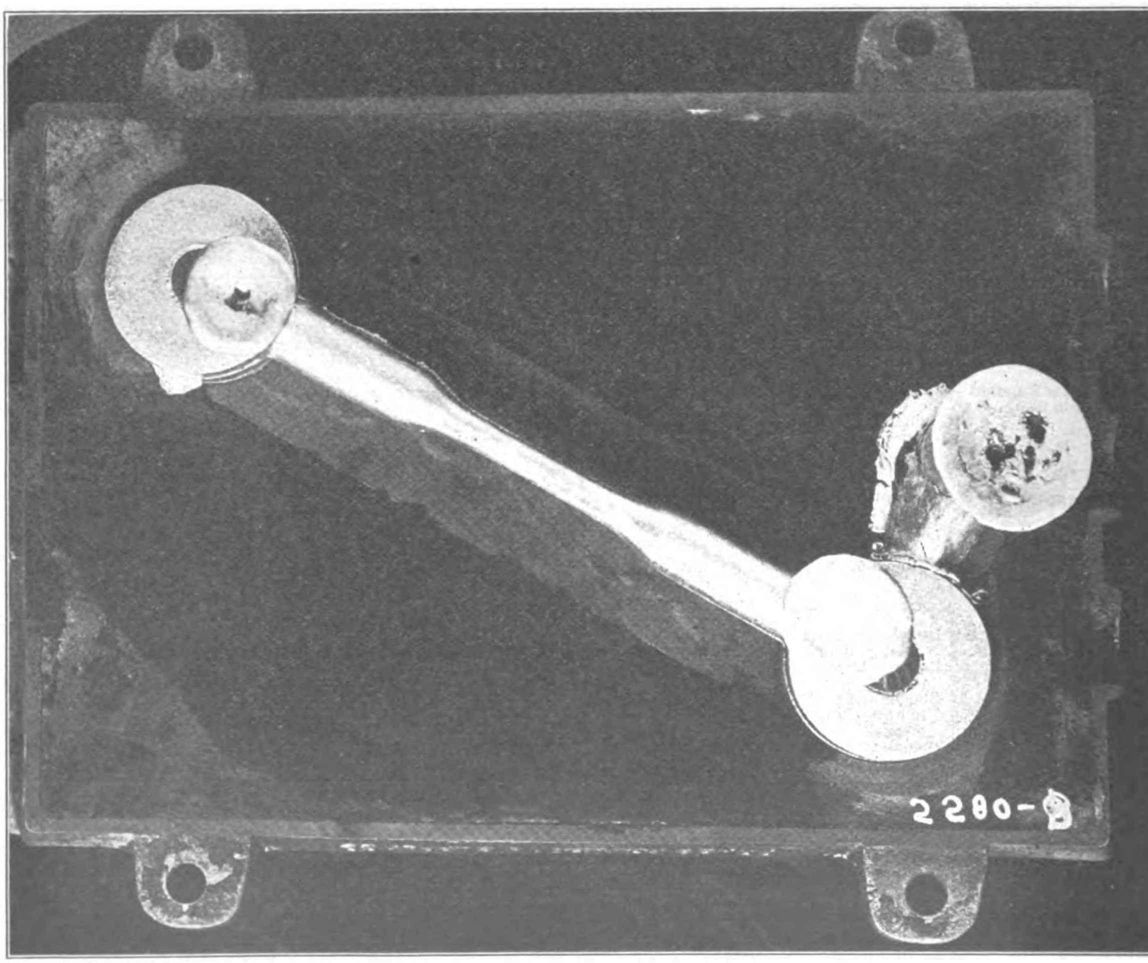


FIG. 2.—Hot shortness test.

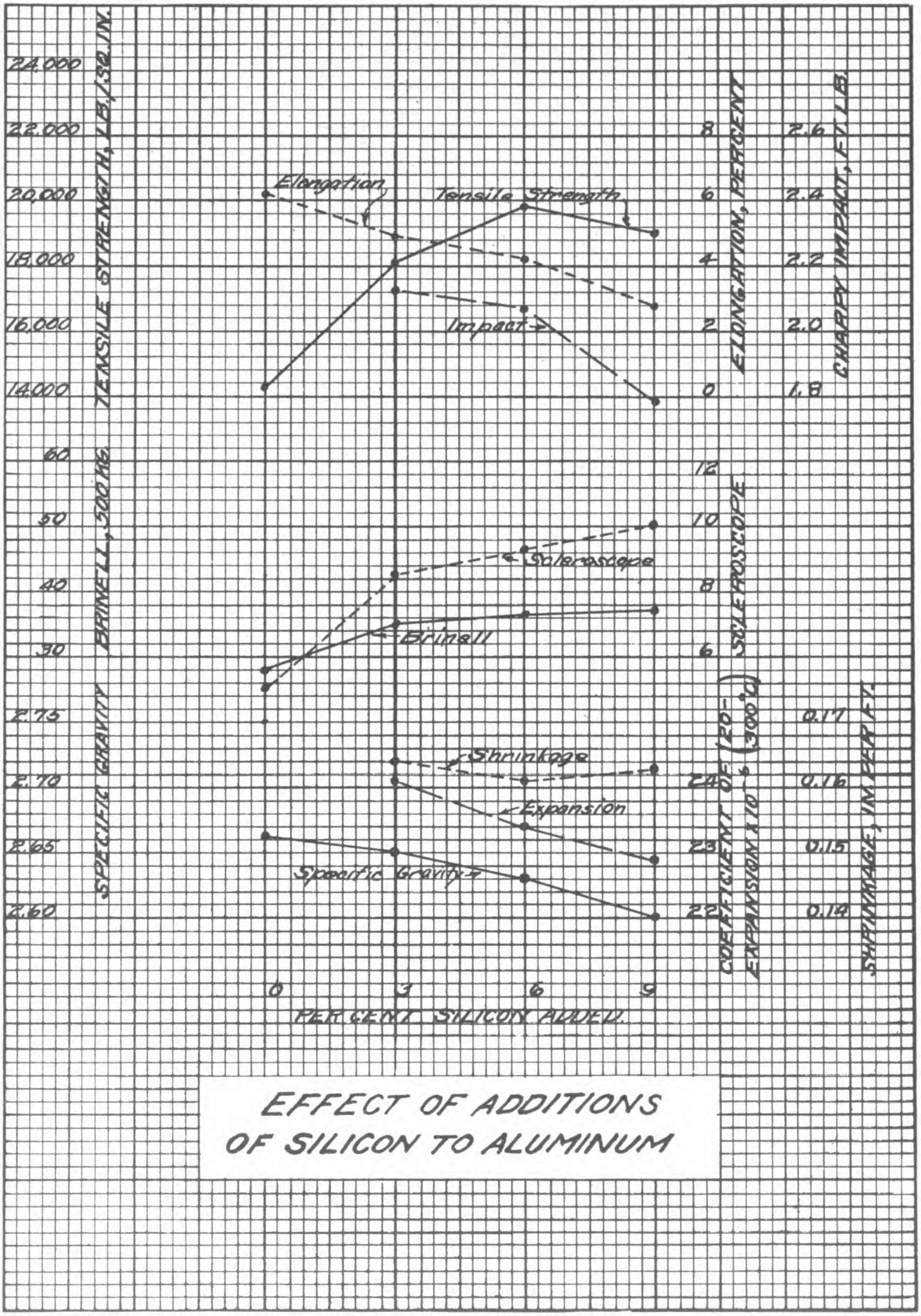
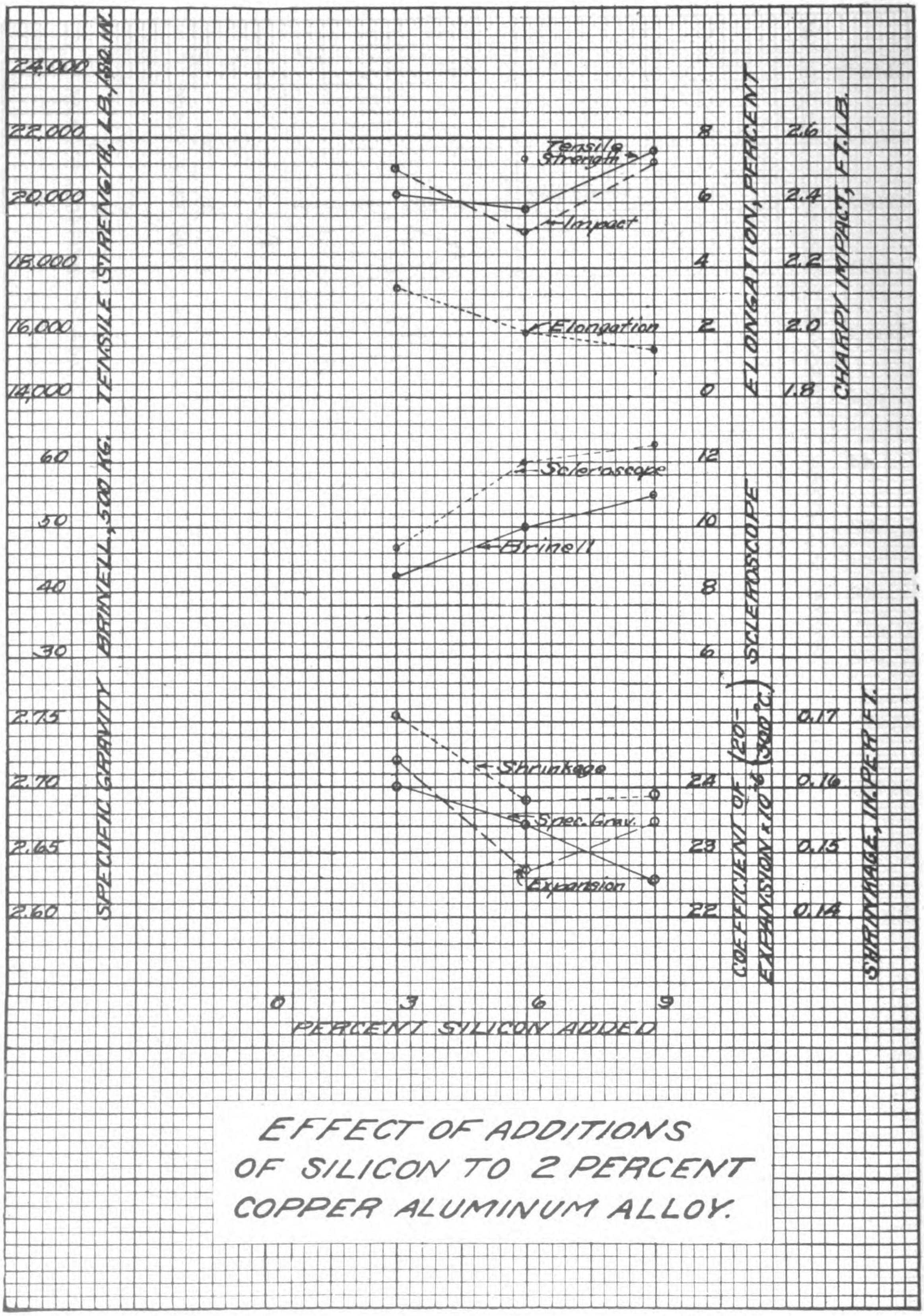

24,000
22,000
20,000
18,000
16,000
14,000
TENSILE STRENGTH, LB./SQ. IN.
60
50
40
30
BRINELL, 500 KG.
2.75
2.70
2.65
2.60
SPECIFIC GRAVITY
Elongation
Tensile Strength
Impact
Scleroscope
Brinell
Shrinkage
Expansion
Specific Gravity
0
3
6
9
PER CENT SILICON ADDED.
8
6
4
2
0
ELONGATION, PERCENT
12
10
8
6
SCLEROSCOPE
24
23
22
COEFFICIENT OF EXPANSION X 10⁻⁶ (20-300°C)
2.6
2.4
2.2
2.0
1.8
CHARPY IMPACT, FT. LB.
0.17
0.16
0.15
0.14
SHRINKAGE, IN. PER FT.
EFFECT OF ADDITIONS
OF SILICON TO ALUMINUM

FIG. 3.



24,000
22,000
20,000
18,000
16,000
14,000
60
50
40
30
2.75
2.70
2.65
2.60
SPECIFIC GRAVITY BRINELL, 500 KG. TENSILE STRENGTH, LB./SQ.IN.
Tensile Strength
Impact
Elongation
Scleroscope
Brinell
Shrinkage
Spec. Grav.
Expansion
8
6
4
2
0
12
10
8
6
24
23
22
2.6
2.4
2.2
2.0
1.8
0.17
0.16
0.15
0.14
ELONGATION, PERCENT
SCLEROSCOPE
COEFFICIENT OF EXPANSION × 10⁻⁶ (20°-300° C.)
CHARPY IMPACT, FT. LB.
SHRINKAGE, IN. PER FT.
0
3
6
9
PERCENT SILICON ADDED
EFFECT OF ADDITIONS OF SILICON TO 2 PERCENT COPPER ALUMINUM ALLOY.

Fig. 4.

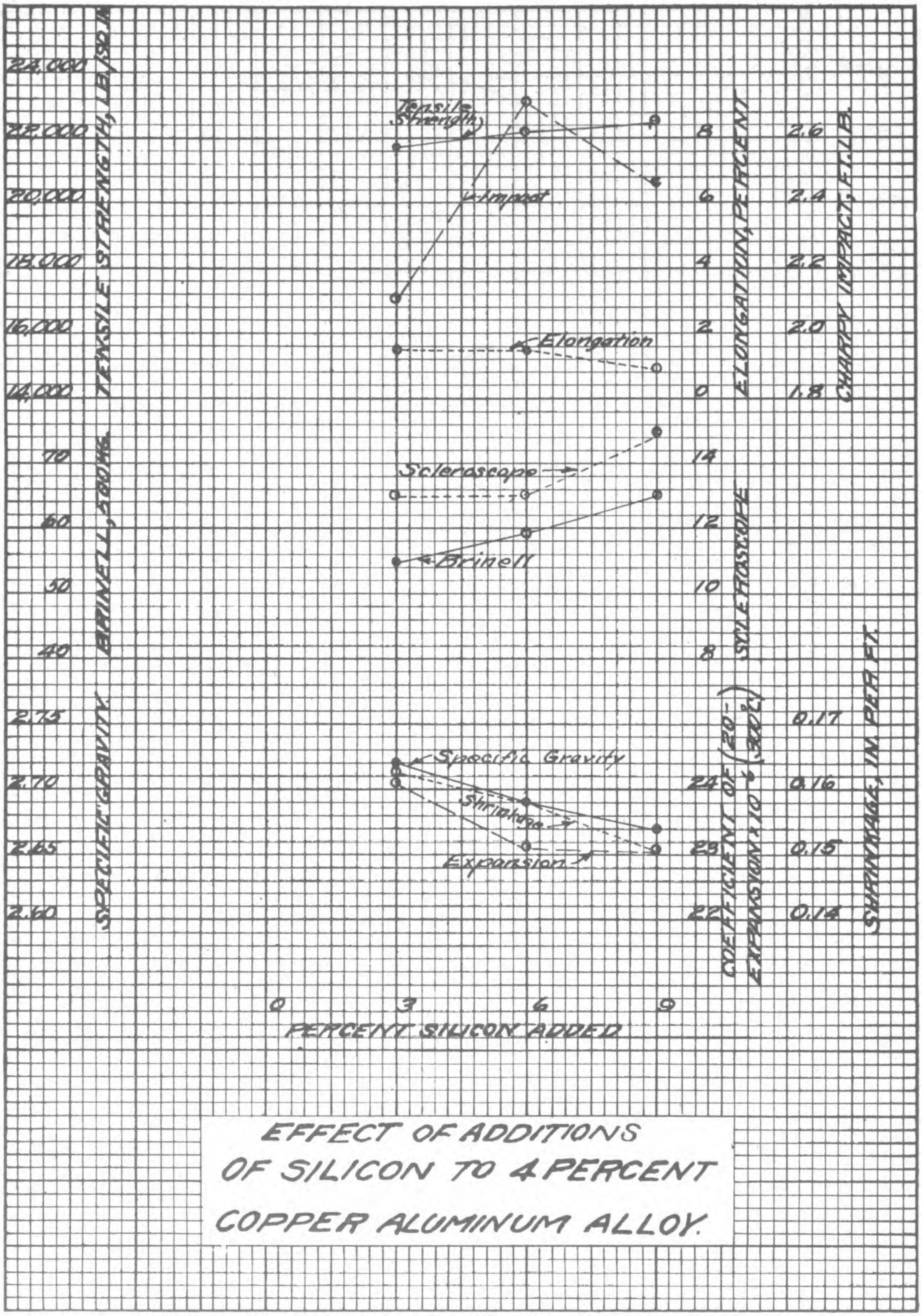

24,000
22,000
20,000
18,000
16,000
14,000
70
60
50
40
2.75
2.70
2.65
2.60
SPECIFIC GRAVITY.
BRINELL, 500 KG.
TENSILE STRENGTH, LB./SQ.IN.
Tensile Strength
Impact
Elongation
Scleroscope
Brinell
Specific Gravity
Shrinkage
Expansion
8
6
4
2
0
14
12
10
8
24
23
22
ELONGATION, PERCENT
SCLEROSCOPE
COEFFICIENT OF EXPANSION × 10⁻⁶ (20°-300°C.)
2.6
2.4
2.2
2.0
1.8
CHARPY IMPACT, FT.LB.
0.17
0.16
0.15
0.14
SHRINKAGE, IN. PER FT.
0
3
6
9
PERCENT SILICON ADDED
EFFECT OF ADDITIONS
OF SILICON TO 4 PERCENT
COPPER ALUMINUM ALLOY.

FIG. 5.

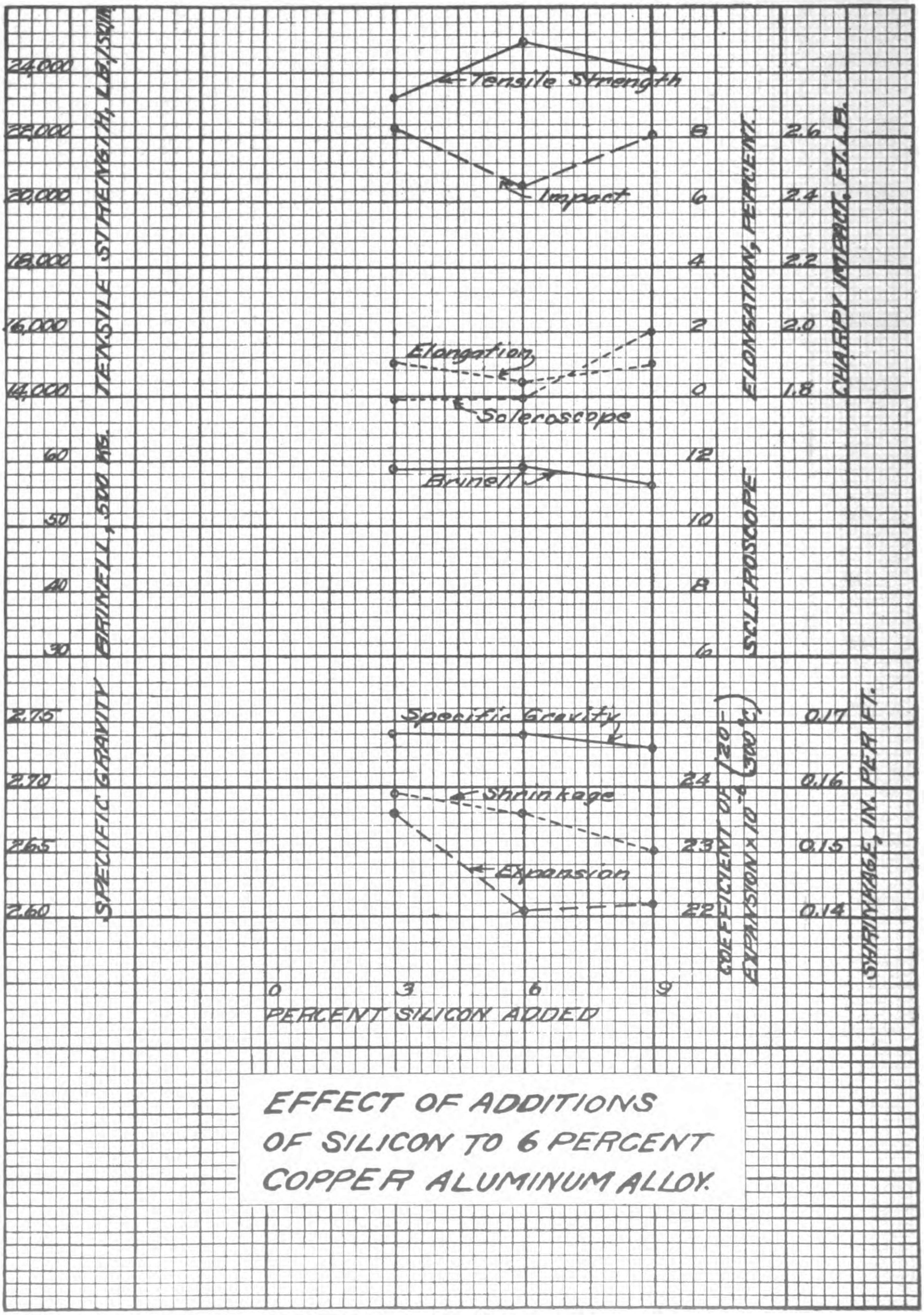
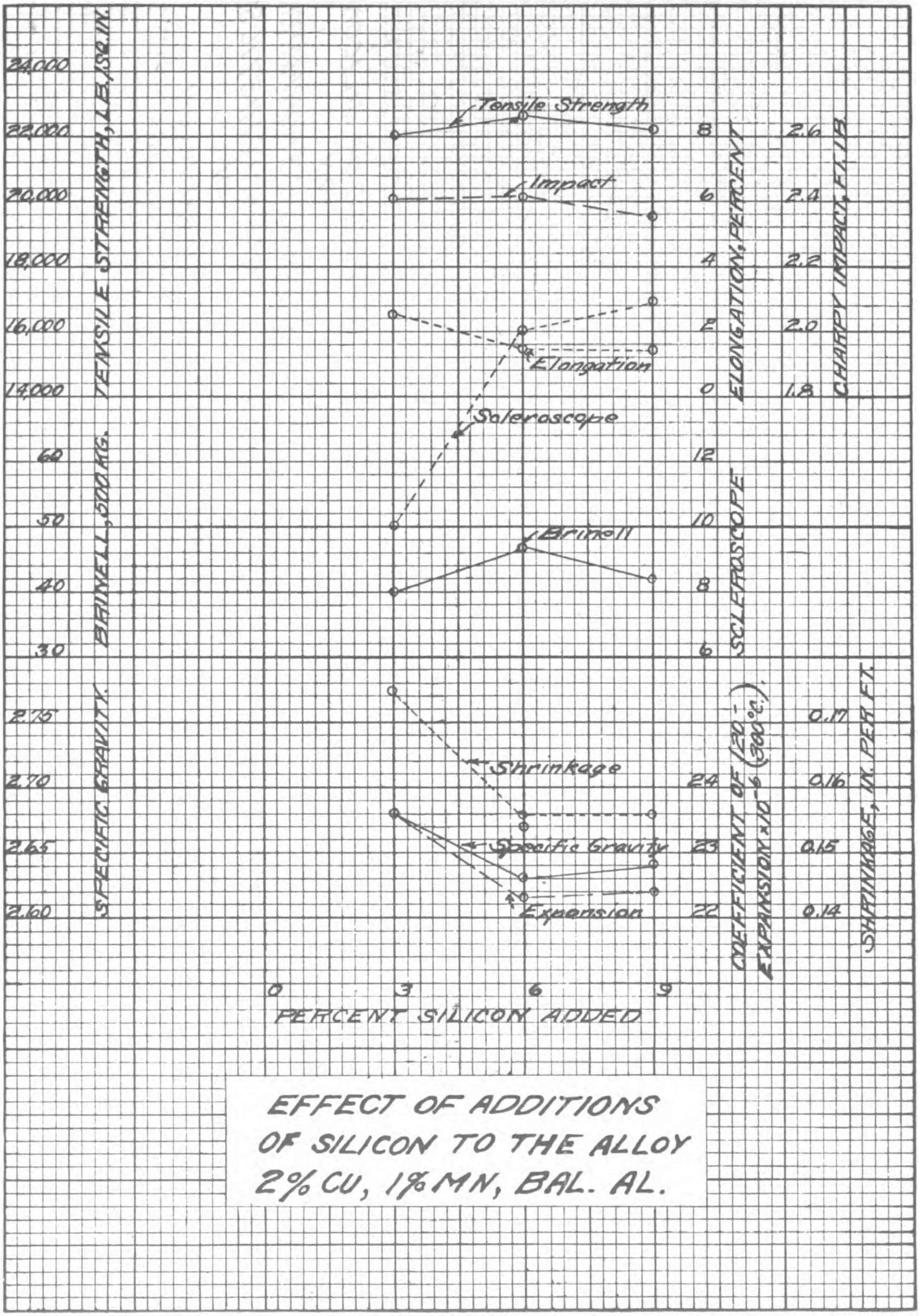

Tensile Strength
Impact
Elongation
Scleroscope
Brinell
Specific Gravity
Shrinkage
Expansion
TENSILE STRENGTH, LB./SQ.IN.
BRINELL, 500 KG.
SPECIFIC GRAVITY
ELONGATION, PERCENT.
SCLEROSCOPE
COEFFICIENT OF EXPANSION × 10⁻⁶ (20°–300°C)
CHARPY IMPACT, FT. LB.
SHRINKAGE, IN. PER FT.
24,000
22,000
20,000
18,000
16,000
14,000
60
50
40
30
2.75
2.70
2.65
2.60
8
6
4
2
0
12
10
8
6
24
23
22
2.6
2.4
2.2
2.0
1.8
0.17
0.16
0.15
0.14
0
3
6
9
PERCENT SILICON ADDED
EFFECT OF ADDITIONS OF SILICON TO 6 PERCENT COPPER ALUMINUM ALLOY.

FIG. 6.



24,000
22,000
20,000
18,000
16,000
14,000
60
50
40
30
2.75
2.70
2.65
2.60
SPECIFIC GRAVITY. BRINELL, 500 KG. TENSILE STRENGTH, LB./SQ.IN.
Tensile Strength
Impact
Elongation
Scleroscope
Brinell
Shrinkage
Specific Gravity
Expansion
8
6
4
2
0
12
10
8
6
24
23
22
2.6
2.4
2.2
2.0
1.8
0.17
0.16
0.15
0.14
ELONGATION, PERCENT
SCLEROSCOPE
CHARPY IMPACT, FT. LB.
COEFFICIENT OF (20°-300°C.) EXPANSION ×10⁻⁶
SHRINKAGE, IN. PER FT.
0
3
6
9
PERCENT SILICON ADDED
EFFECT OF ADDITIONS
OF SILICON TO THE ALLOY
2% CU, 1% MN, BAL. AL.

FIG. 7.

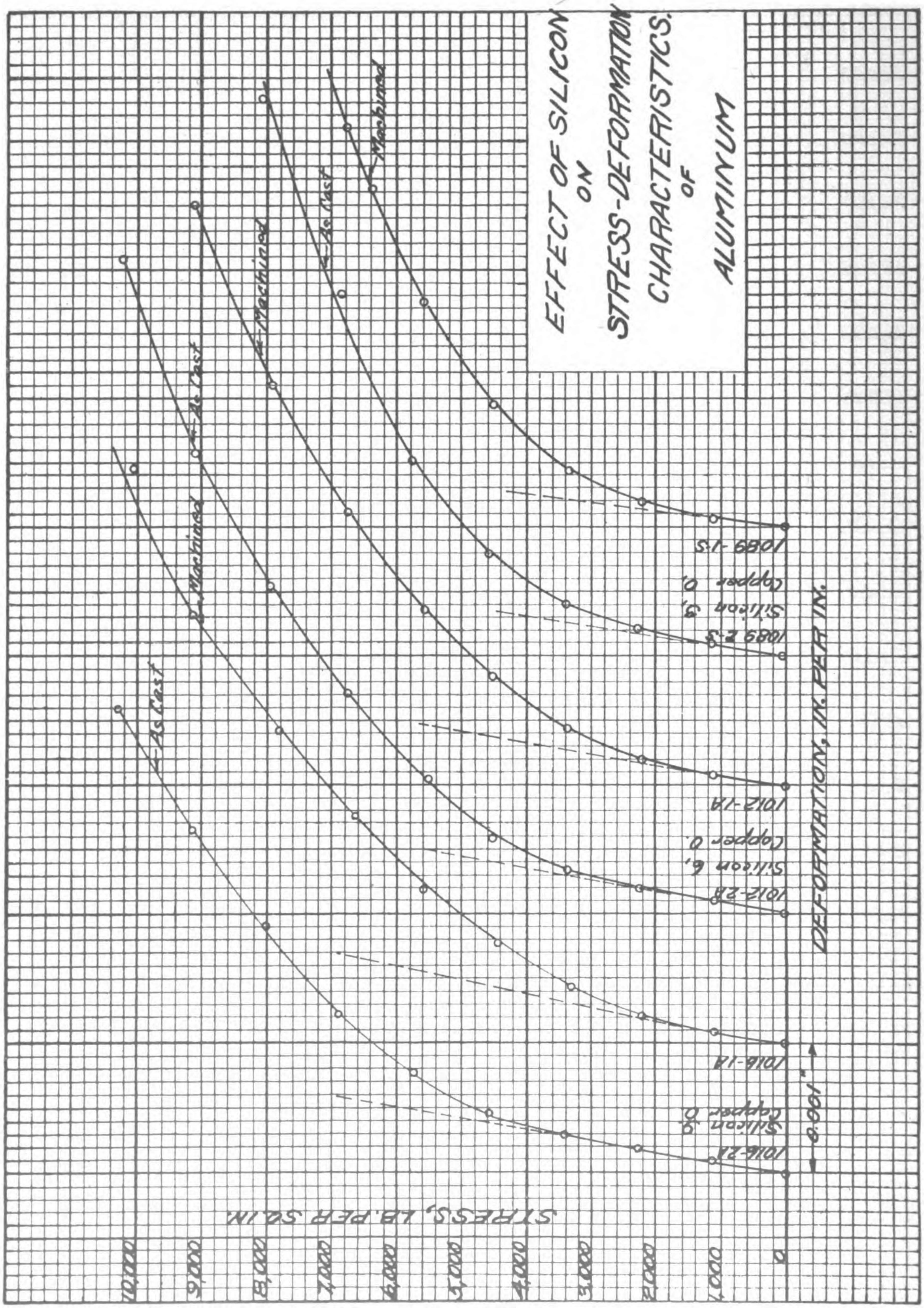

EFFECT OF SILICON
ON
STRESS-DEFORMATION
CHARACTERISTICS
OF
ALUMINUM
STRESS, LB. PER SQ. IN.
DEFORMATION, IN. PER IN.
0.001"
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
1089-1S
Silicon .9,
Copper 0.
1089-2S
1012-1A
Silicon 6,
Copper 0.
1012-2A
1016-1A
1016-2A
As Cast
Machined

FIG. 8.

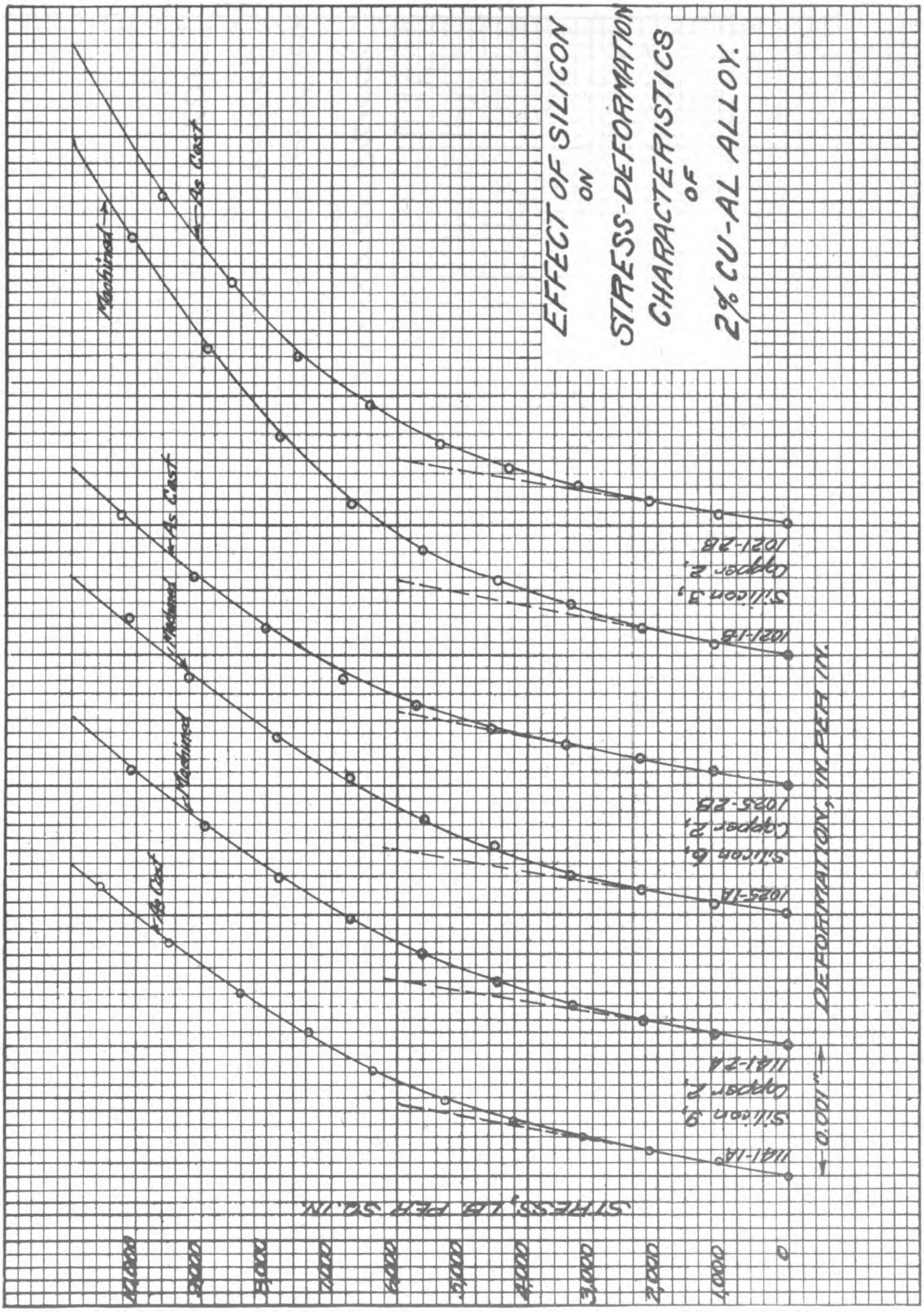

EFFECT OF SILICON ON STRESS-DEFORMATION CHARACTERISTICS OF 2% CU-AL ALLOY.
Machined
As Cast
Silicon 3, Copper 2, 1021-2B
1021-1B
Silicon 6, Copper 2, 1025-2B
1025-1B
Silicon 9, Copper 2, 1121-2A
1121-1A
STRESS, LB PER SQ. IN.
DEFORMATION, IN. PER IN.
0.001"
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000

Fig. 9.

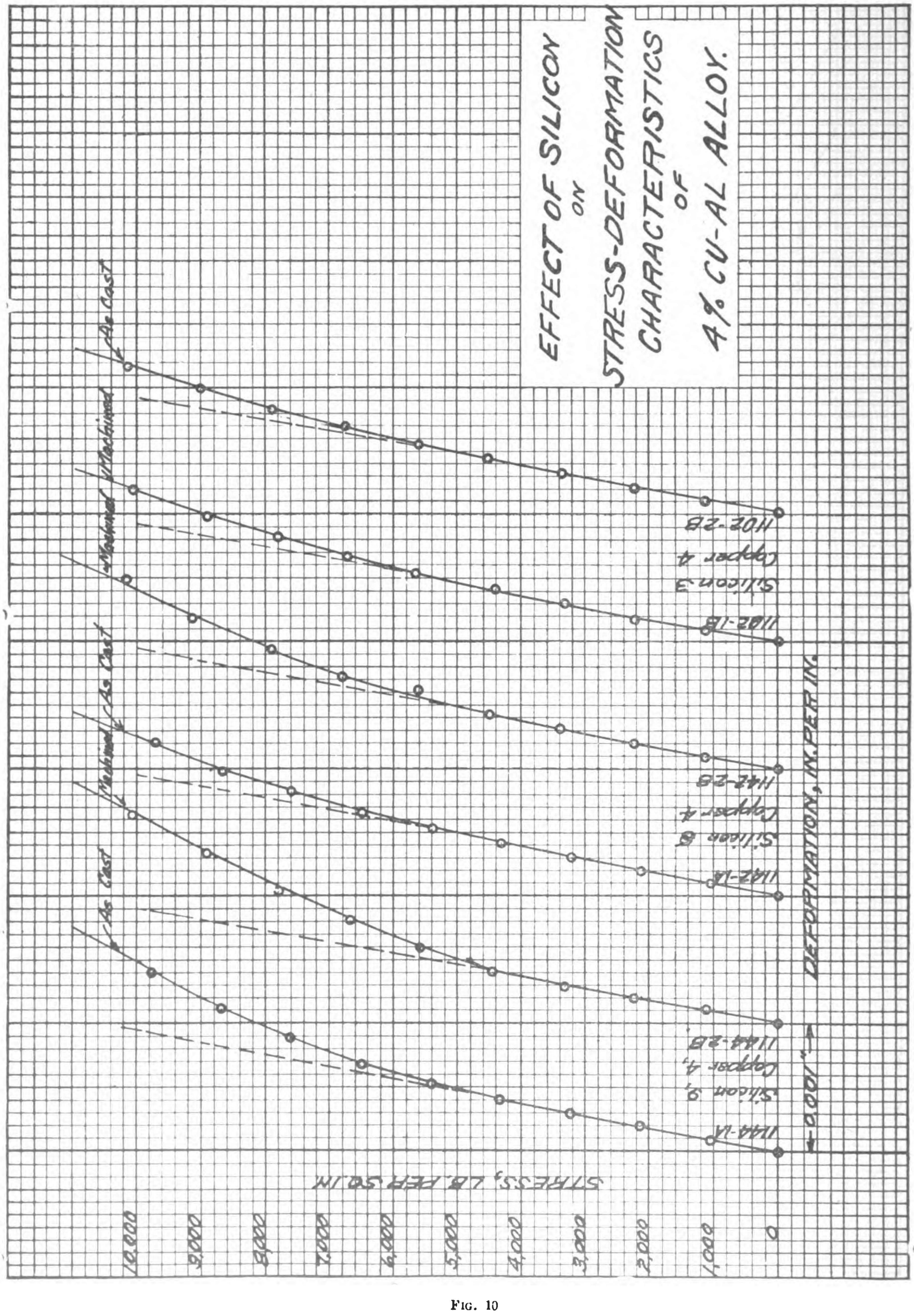

EFFECT OF SILICON ON STRESS-DEFORMATION CHARACTERISTICS OF 4% CU-AL ALLOY.
As Cast
Machined
1102-2B
Copper 4
Silicon 3
1102-1B
1142-2B
Copper 4
Silicon 6
1142-1B
1144-2B
Copper 4,
Silicon 9,
1144-1A
DEFORMATION, IN. PER IN.
0.001"
STRESS, LB. PER SQ. IN.
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0

FIG. 10

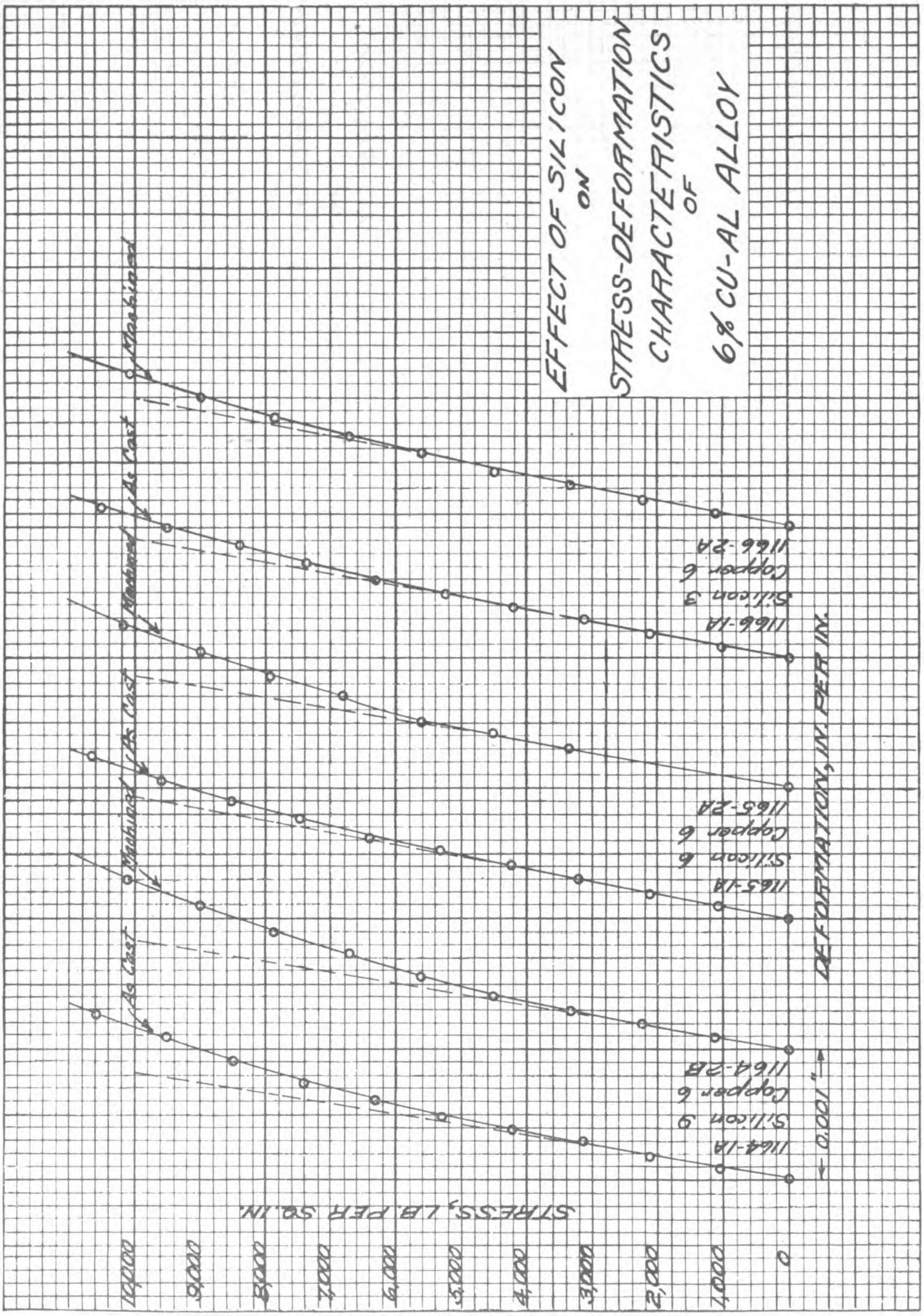

EFFECT OF SILICON ON STRESS-DEFORMATION CHARACTERISTICS OF 6% CU-AL ALLOY
STRESS, LB. PER SQ. IN.
DEFORMATION, IN. PER IN.
0.001"
1166-1A Silicon 3 Copper 6 1166-2A
1165-1A Silicon 6 Copper 6 1165-2A
1164-1A Silicon 9 Copper 6 1164-2B
Machined
As Cast
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0

FIG. 11.

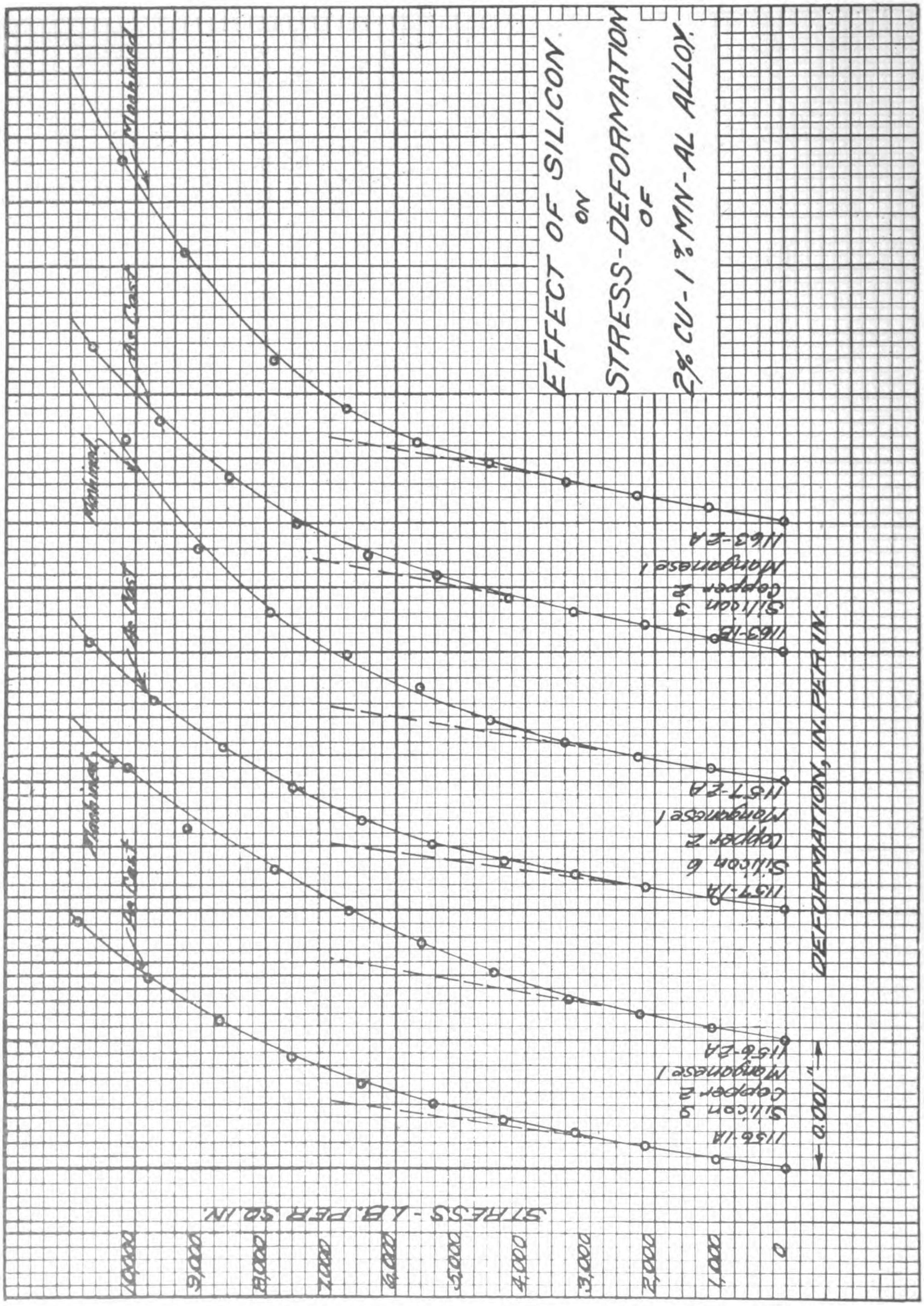

EFFECT OF SILICON
ON
STRESS-DEFORMATION
OF
2% CU-1% MN-AL ALLOY.
Machined
As Cast
Machined
As Cast
Machined
As Cast
1163-1B
Silicon 4
Copper 2
Manganese 1
1163-2A
1157-1A
Silicon 6
Copper 2
Manganese 1
1157-2A
1156-1A
Silicon 2
Copper 2
Manganese 1
1156-2A
0.001"
DEFORMATION, IN. PER IN.
STRESS - LB. PER SQ. IN.
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000

FIG. 12.

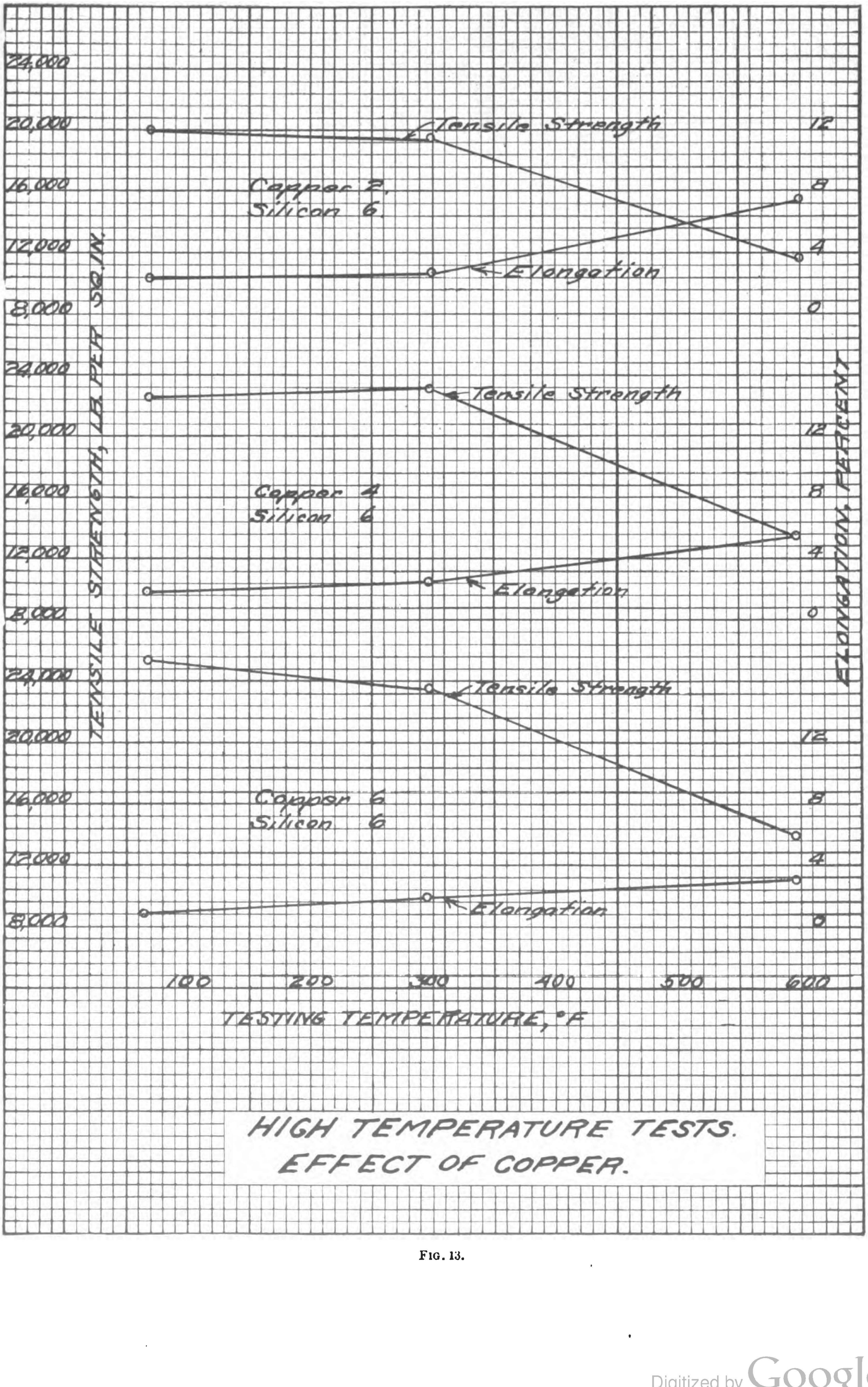
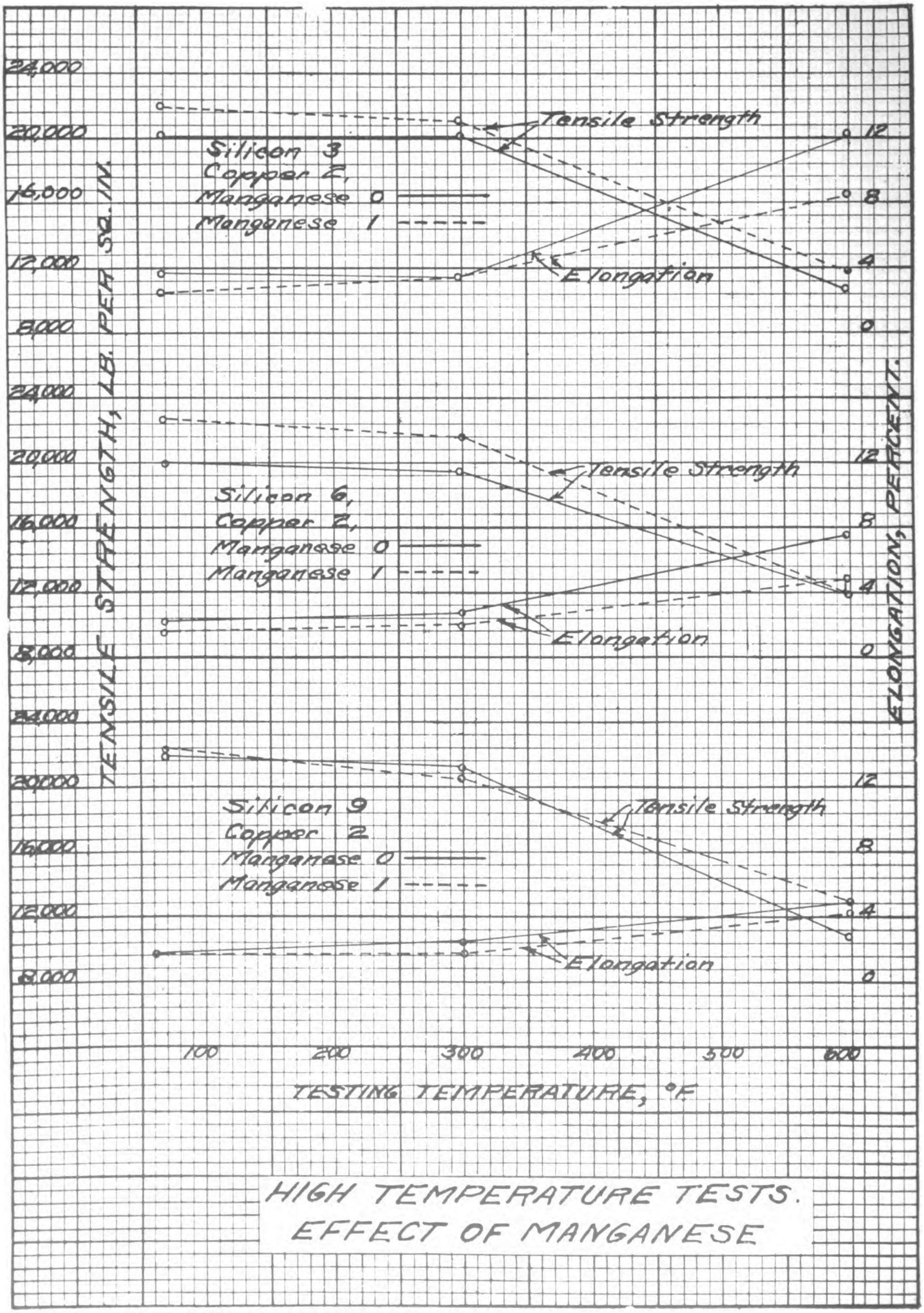
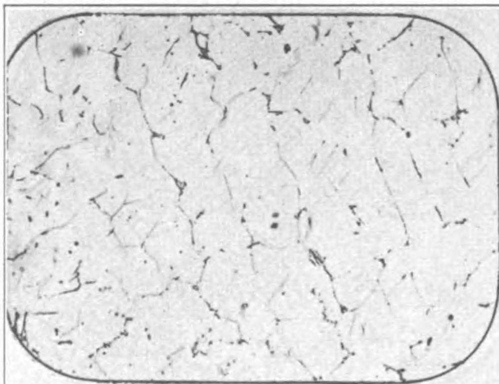

HIGH TEMPERATURE TESTS.
EFFECT OF COPPER.
TENSILE STRENGTH, LB. PER SQ. IN.
ELONGATION, PERCENT
TESTING TEMPERATURE, °F
Copper 2, Silicon 6.
Copper 4 Silicon 6
Copper 6 Silicon 6
Tensile Strength
Elongation
24,000
20,000
16,000
12,000
8,000
100
200
300
400
500
600
12
8
4
0

FIG. 13.



Tensile Strength
Silicon 3
Copper 2,
Manganese 0
Manganese 1
Elongation
Tensile Strength
Silicon 6,
Copper 2,
Manganese 0
Manganese 1
Elongation
Tensile Strength
Silicon 9
Copper 2
Manganese 0
Manganese 1
Elongation
TENSILE STRENGTH, LB. PER SQ. IN.
24,000
20,000
16,000
12,000
8,000
ELONGATION, PERCENT.
12
8
4
0
100
200
300
400
500
600
TESTING TEMPERATURE, °F
HIGH TEMPERATURE TESTS.
EFFECT OF MANGANESE

FIG. 14.

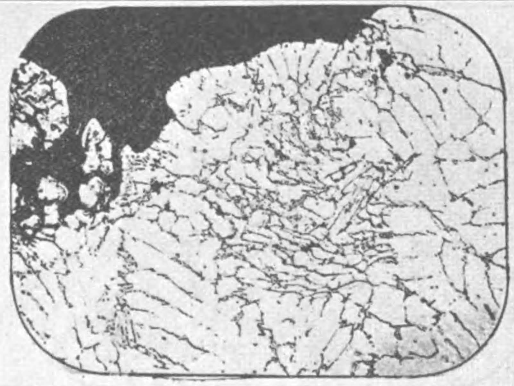


(a) 100 X
Aluminum solid solution matrix and network of impurities.

(b) 500 X
Needles, probably $FeAl_3$, and Si eutectic (black).

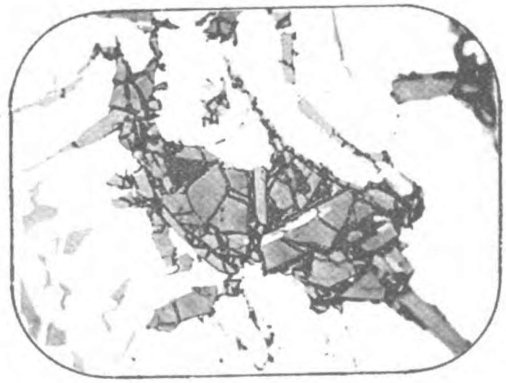
(c) 1000 X
Shows contrast between $FeAl_3$ needles (light) and Si eutectic particles (black).

Fig. 15 - Normal Structure.



(a) 100 X
Impurities segregated near pipe at centre of test specimen. Compare Fig. 15-A.

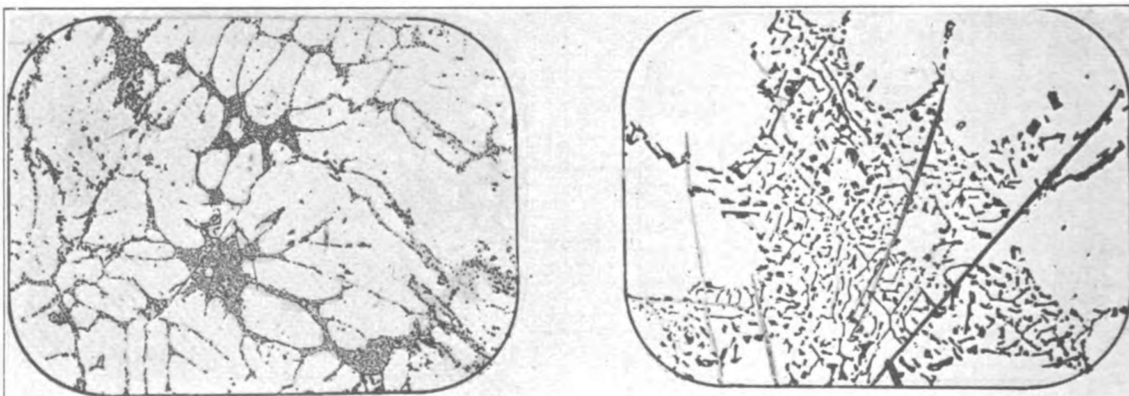
(b) 500 X
Shows nature of network in this segregated area.



(c) 1000 X
Probably "X constituent," containing Fe and Si. Appears same color as needles in Fig. 15-C and has same etching characteristics.

Fig. 16 - Segregated Area.

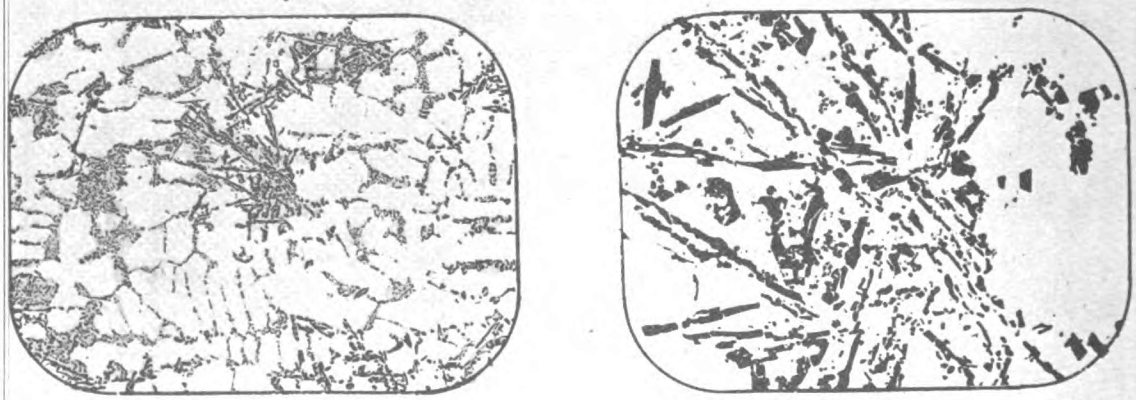
Unetched.
Structure of 3/4 in. diameter sand cast test bar of aluminum ingot (Melt 920, Si 0.99, Cu 0.32, Fe 0.51).



(a) 100 X
Average Structure.

(b) 500 X
Si-Al eutectic and light needles probably $FeAl_3$.

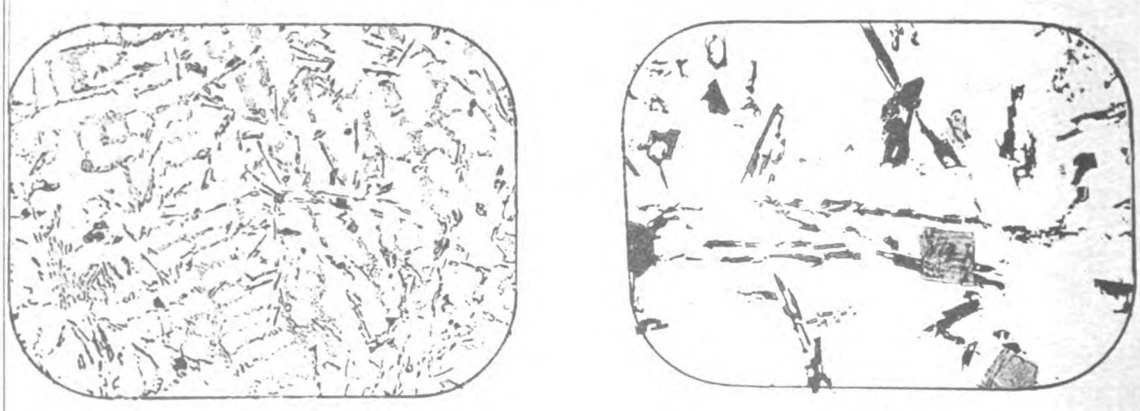
Fig. 17 (Melt 1010, Cu 0.41, Si 4.12, Fe 0.59).



(a) 100 X
Average Structure.

(b) 500 X
Coarse Si-Al eutectic, see centre of Fig. 18-A.

Fig. 18 (Melt 1012, Cu 0.42, Si 6.20, Fe 0.90).

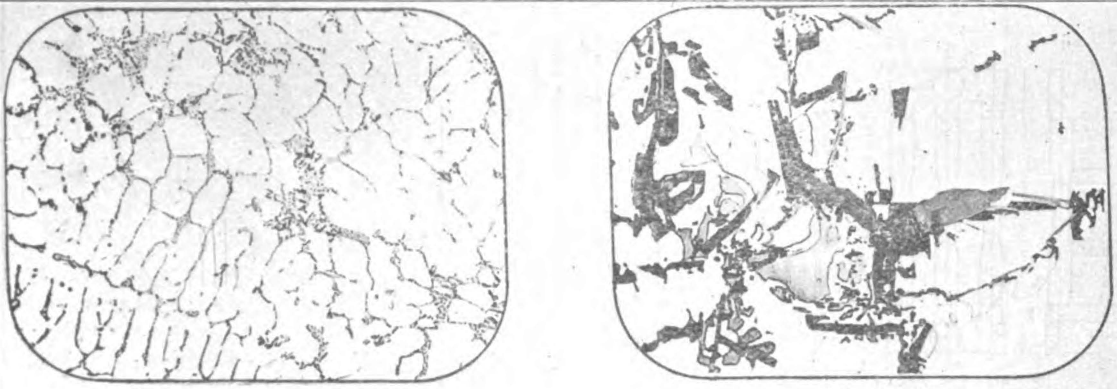


(a) 100 X
Average Structure.

(b) 500 X
Particles of Si eutectic dark and lighter cubes of unknown composition.

Fig. 19 (Melt 1016, Cu 0.34, Si 5.34, Fe 0.73).

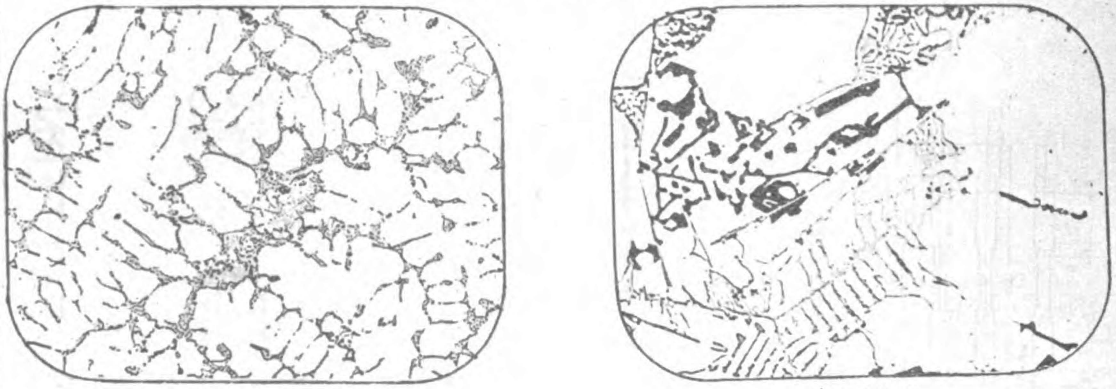
Structure of 3/4 in. diameter sand cast test specimens of the Silicon-Aluminum Alloys.



(a) 100 X
Average Structure.

(b) 500 X
Black, Si; half tone probably $FeAl_3$ or "X Const.;"light, $CuAl_2$; matrix, aluminum solid solution.

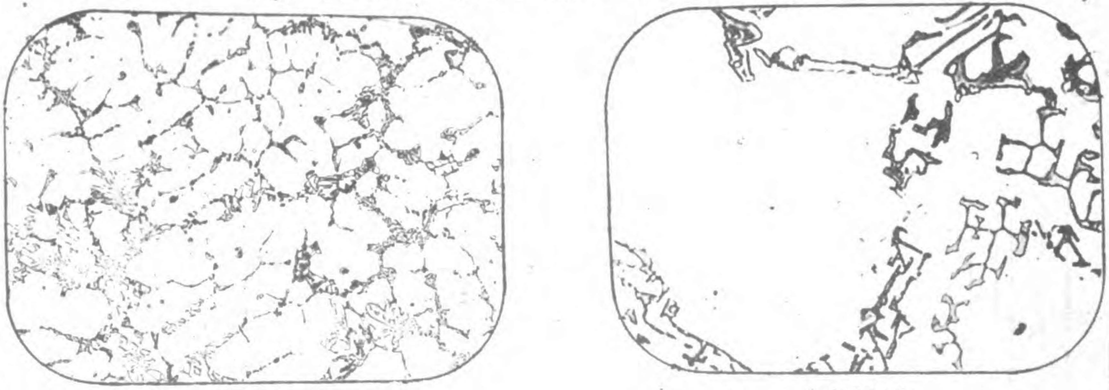
Fig. 20 (Melt 1036, Cu 4.25, Si 3.41, Fe 0.74).



(a) 100 X
Average Structure.

(b) 500 X
Si, black; light rounded particles, $CuAl_2$; dendritic structure, probably $FeAl_3$ or "X Const.;" needles probably $FeAl_3$.

Fig. 21 (Melt 1C48, Cu 6.39, Si 3.90, FeC.77).



(a) 100 X
Average Stfucture.

(b) 500 X
Characteristic swastika form of constituent which appears with addition of manganese.

Fig. 22 (Melt 1071, Cu 2.33, Si 3.86, Fe 0.65, Mn 0.87).

Structure of 3/4 in. diameter sand cast test specimens of the Copper-Silicon-Aluminum Alloys with and without Manganese.

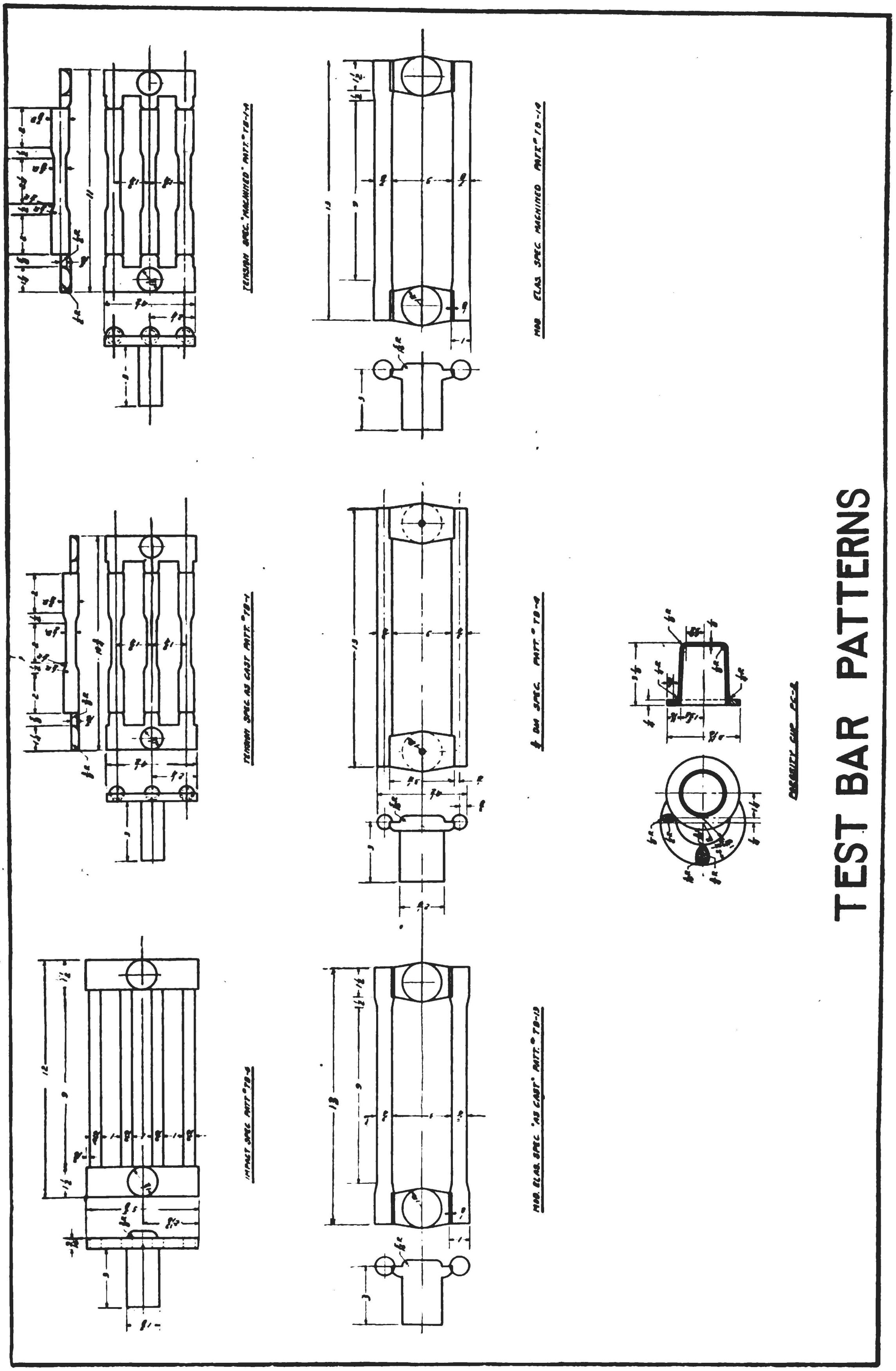


FIG. 23.

ADDENDUM I.

AGING TESTS ON COPPER-SILICON-ALUMINUM ALLOYS.

The following table gives a summary of the aging tests made on some of the copper-silicon-aluminum alloys which were investigated in this report. The figures for the "As cast," the 9 months' aging, and the 15 months' aging tests are the averages of five tension tests; and the figures for the 30 days' aging are the averages of three tension tests.

These results show that there is no noticeable change in tensile properties with time after casting in the copper-silicon-aluminum alloys containing up to 6 per cent copper and 9 per cent silicon.

AGING TESTS.

	"As cast."	30 days' aging.	9 months' aging.	15 months' aging.
Melt No. 1010—Cu 0.41, Si 4.12, Fe 0.59.				
Tensile strength, pounds per square inch	18,120	19,520	19,260	19,250
Elongation, per cent in 2 inches	4.9	5.3	4.0	4.5
Melt No. 1012—Cu 0.42, Si 6.20, Fe 0.90.				
Tensile strength, pounds per square inch	19,800	21,520	19,800	20,810
Elongation, per cent in 2 inches	4.2	4.2	4.25	4.5
Melt No. 1016—Cu 0.34, Si 9.34, Fe 0.73.				
Tensile strength, pounds per square inch	18,980	20,120	18,430	18,840
Elongation, per cent in 2 inches	2.8	2.5	3.0	2.5
Melt No. 1036—Cu 4.25, Si 3.41, Fe 0.74.				
Tensile strength, pounds per square inch	21,740	23,970	23,360	22,440
Elongation, per cent in 2 inches	2.2	1.7	1.5	1.0
Melt No. 1044—Cu 4.26, Si 10.12, Fe 0.70.				
Tensile strength, pounds per square inch	22,540	23,640	23,850	24,990
Elongation, per cent in 2 inches	0.9	0.5	1.3	1.0
Melt No. 1048—Cu 6.39, Si 3.90, Fe 0.77.				
Tensile strength, pounds per square inch	23,210	23,380	27,260	26,930
Elongation, per cent in 2 inches	0.9	1.0	1.16	0.5
Melt No. 1069—Cu 6.29, Si 9.00, Fe 0.66.				
Tensile strength, pounds per square inch	24,170	24,990	25,020	25,570
Elongation, per cent in 2 inches	1.0	1.3	1.0	0.5

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